Airborne Particulate Monitoring

Greg Smallwood

Renewable Energy and Climate Science for the Americas: Metrology and Technology Challenges

8-9 Oct 2013 Querétaro, México

Acknowledgements

Jeff Brook	Environment Canada
Allan Bertram	University of British Columbia
Greg Evans	University of Toronto
Jason Olfert	University of Alberta
Adam Boies	University of Cambridge

Kevin Thomson and the entire Black Carbon Metrology Team at NRC Measurement Science and Standards

Overview

Questions to be addressed:

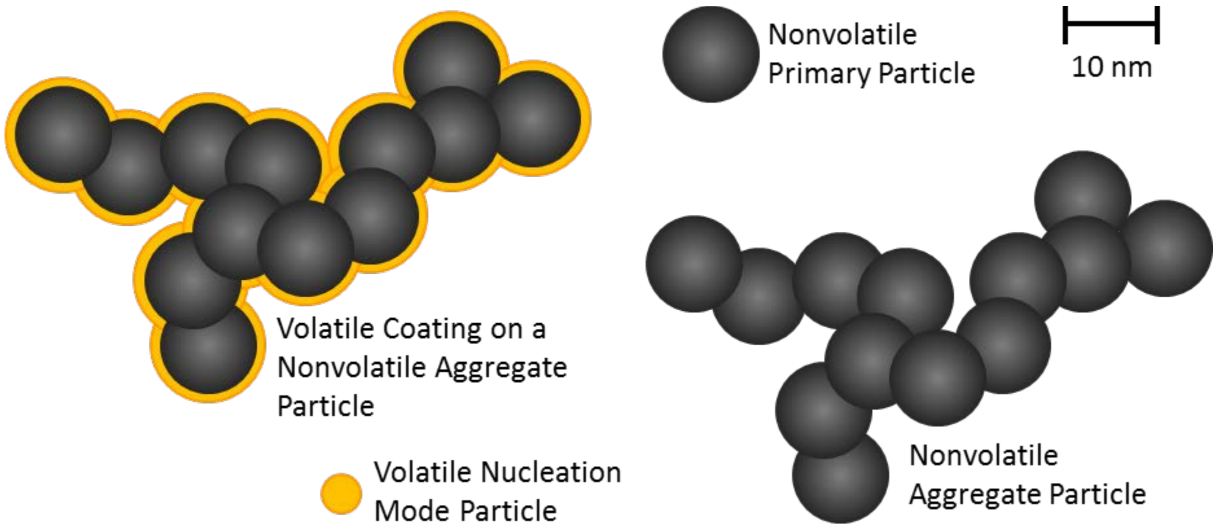
- What are airborne particulates?
- What is the relevance of airborne particulates?
- What needs to be measured?
- What is the Canadian perspective on research and monitoring of airborne particulates?
- What is Canada doing about the measurement of black carbon?

Allan Bertram, University of British Columbia

What are Airborne Particulates?

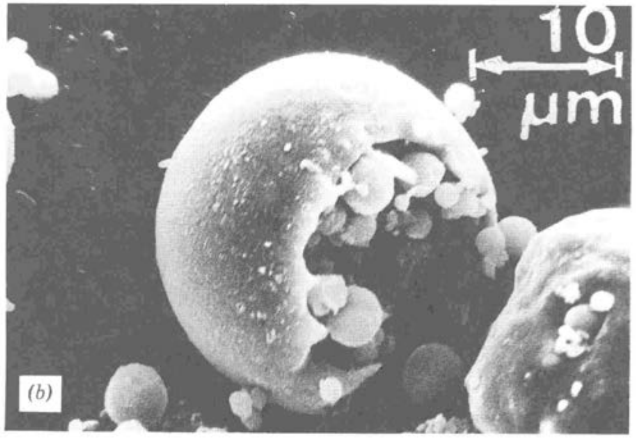
Description

- airborne particulates are referred to as aerosols, nanoaerosols, particulate matter (PM)
- exist as a condensed phase in a gaseous medium
- can be liquid or solid, and volatile, semi-volatile, or nonvolatile

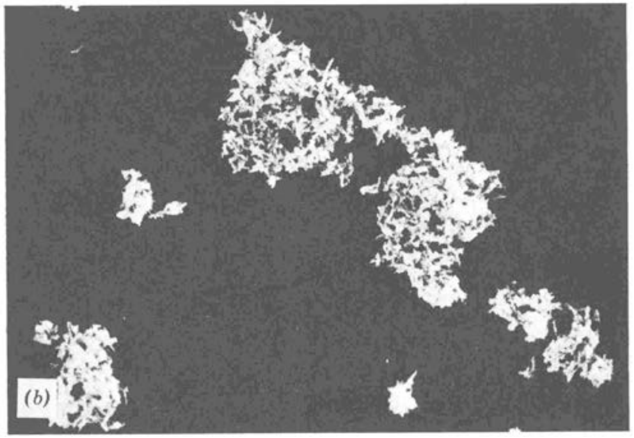


NRC·CNRC

Examples of Particulate Matter (PM)

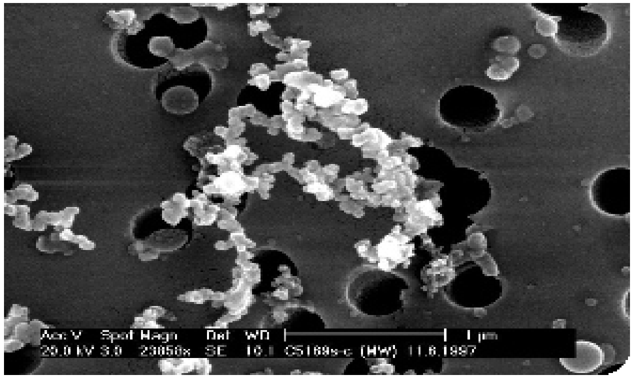


Coal fly ash (~10 µm)



Iron-oxide particles from arc welding (~10 µm)

Los Angeles
Smog (~1-1000 nm)



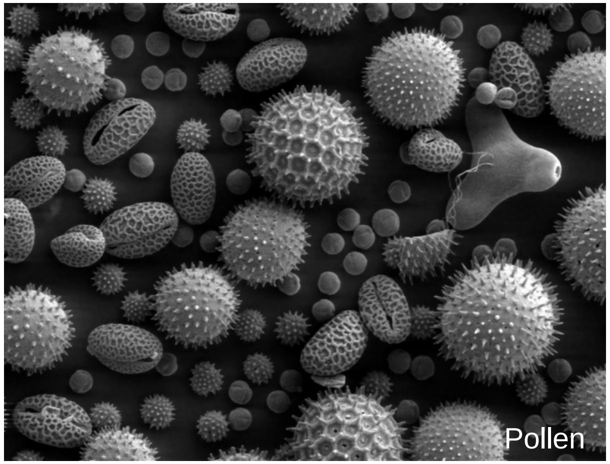
Diesel soot particles (~100 nm)

Jason Olfert, University of Alberta

Natural/Biogenic Sources

Forest fires, volcanoes, soil dust, sea salt, botanical debris…

Forest fire in Montana



Pollen

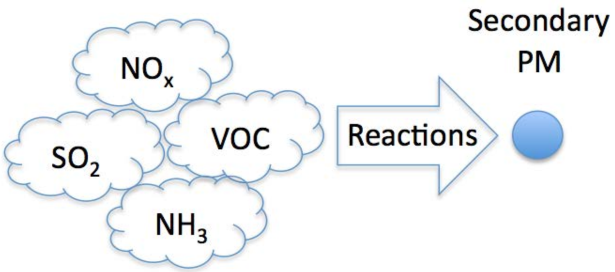
Eruption of Mount St. Helens

Sand-storm in Iraq

Jason Olfert, University of Alberta

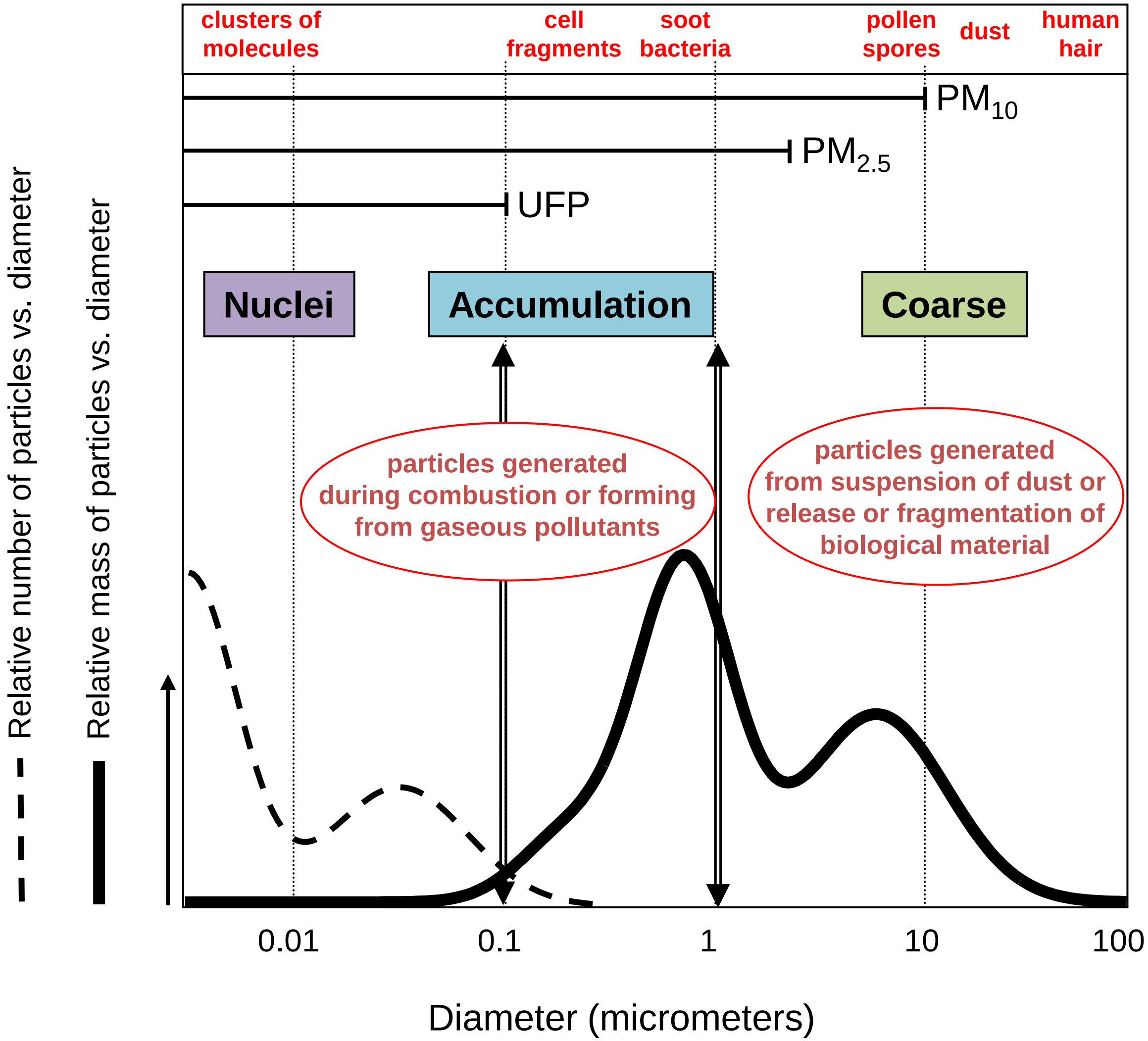
Anthropogenic Sources

Power plants, automobiles (engine exhaust, tires, brakes etc), fireplaces, deep-fryers, aircraft, inhalers...



Jason Olfert, University of Alberta

Airborne Particles Come in a Variety of Sizes



Sizes

- 1 nm – 100 µm in diameter

Concentrations

- 10^6-10^9 particles/cm^3 in urban environments
- 10^2 particles/cm^3 remote regions

Jeff Brook, Environment Canada

Atmospheric Particle Composition

Elemental carbon particles:

- produced during combustion

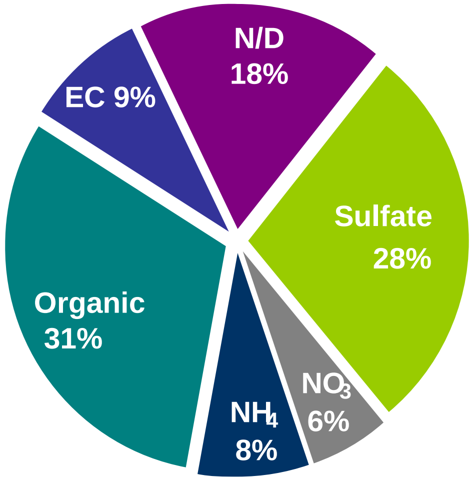
Organic particles:

- primary organic particles
  - emitted directly to the atmosphere
- secondary organic particles
  - formed in the atmosphere by oxidation and condensation of volatile organic carbon
  - often requires photochemistry

Sulfates

- ammonium sulfate particles
- mixed ammonium sulfate-organic particles

Nitrates



Typical Chemical Composition of Fine Aerosol (<1μm) in an Urban Area [Heintzenberg, 1989]

EC = Elemental carbon particles
N/D = not determined

Allan Bertram, University of British Columbia

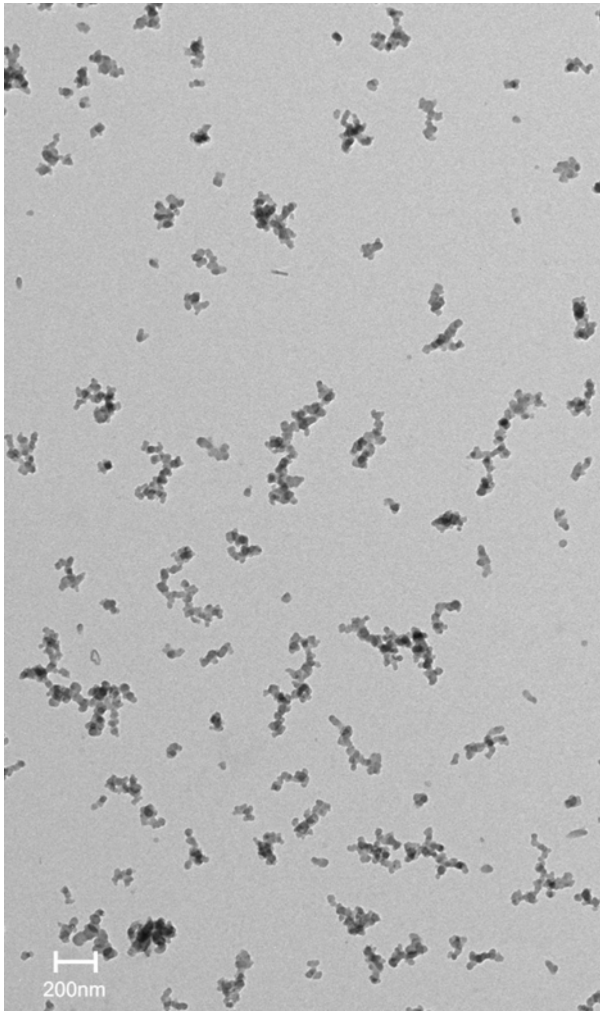
What is the relevance of airborne particulates?

Air Quality

- Human Health
- Visibility

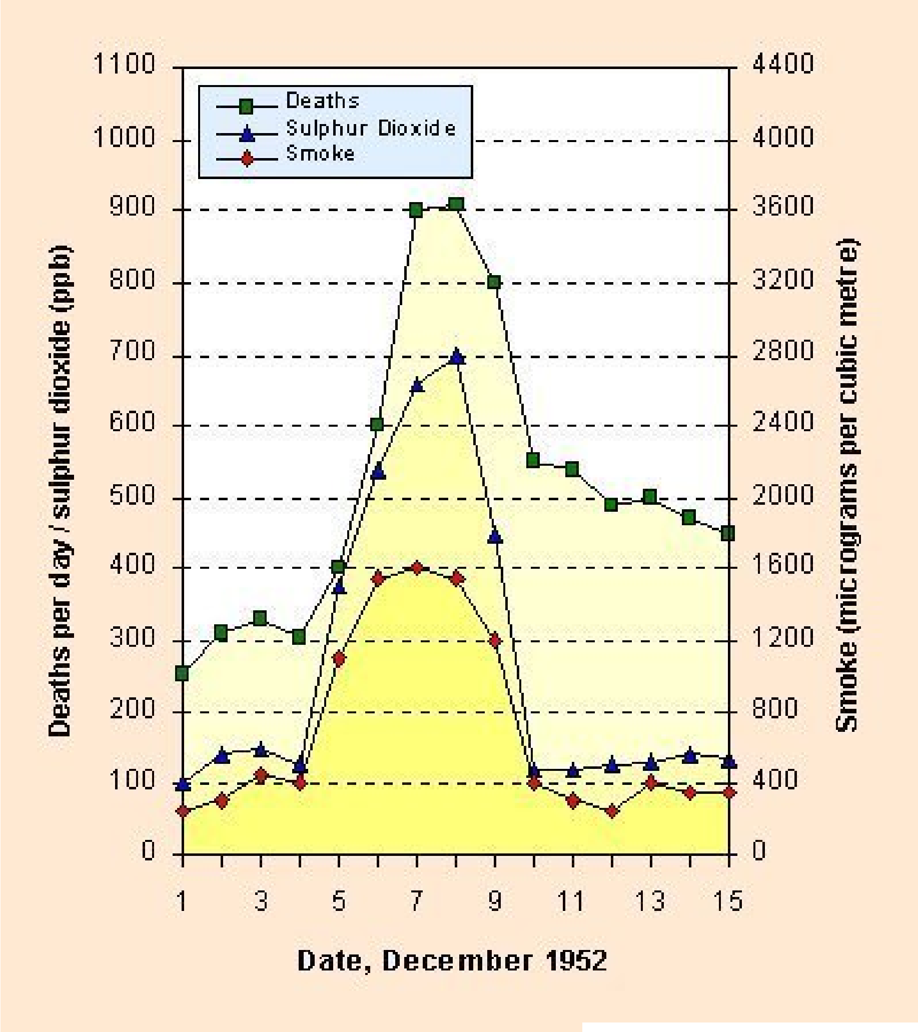
Climate Impacts

Quality of Life and Economic Impacts



Trigger for Health Effects of Airborne Particulates

London Smog Episode:
5-9 Dec 1952

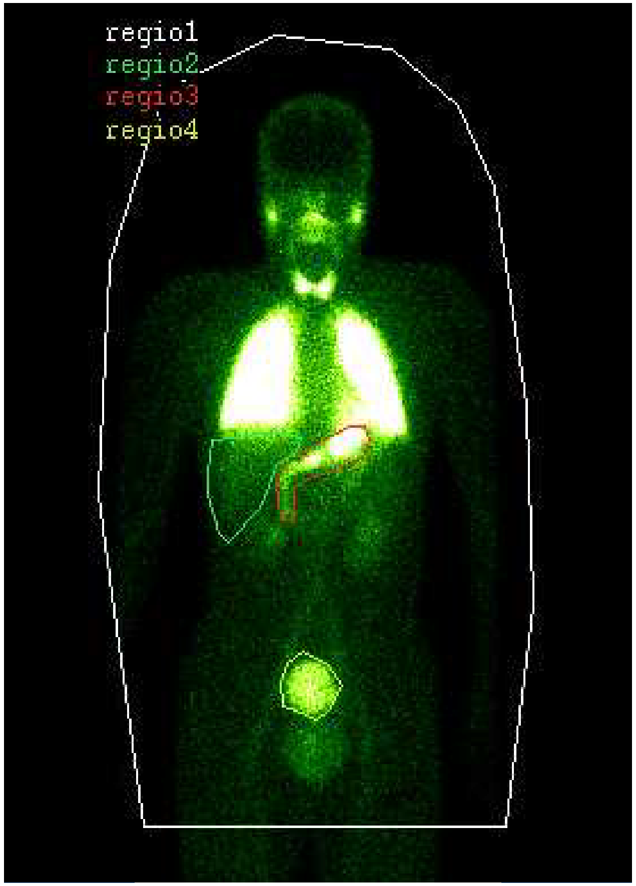


Greg Evans, University of Toronto

Air Quality and Toxicology

Toxicity is dependent on particle size

- different sizes of particles deposit in different area of the respiratory tract
- epidemiological studies have shown that acute exposure to high levels of ambient PM increase mortality rates about 1% for every 5 μg/m^3 increase in $PM_{2.5}$
- about 70% of these deaths are due to cardiovascular disease, and 30% due to respiratory
- also increases in hospitalizations due to asthma and other respiratory diseases

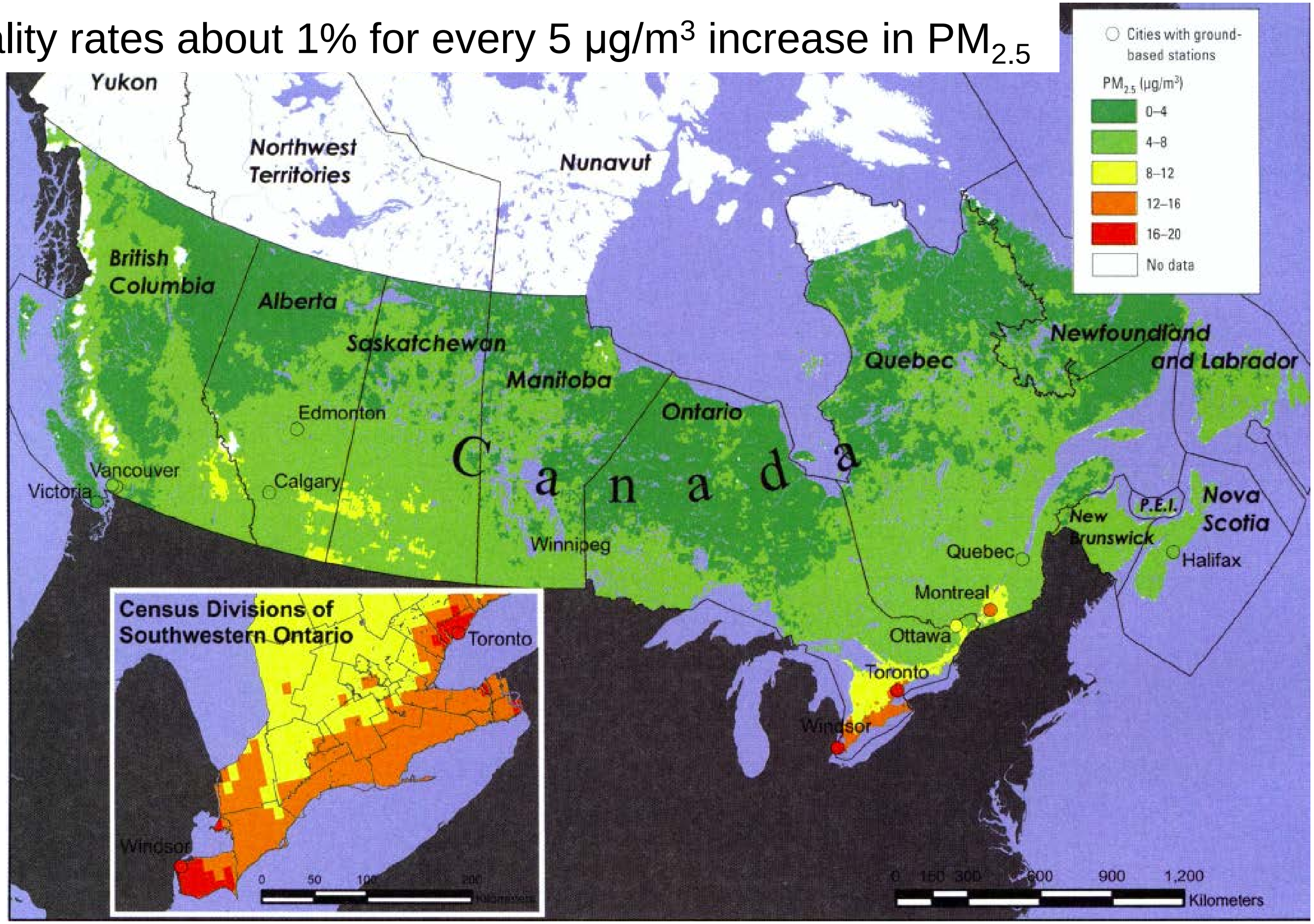


Nemmar et al., Circulation, 2002

Gamma camera image shows particles accumulate in the nasal passages, lungs, liver, and bladder in minutes

$PM_{2.5}$ exposure and cardiovascular mortality: Canada

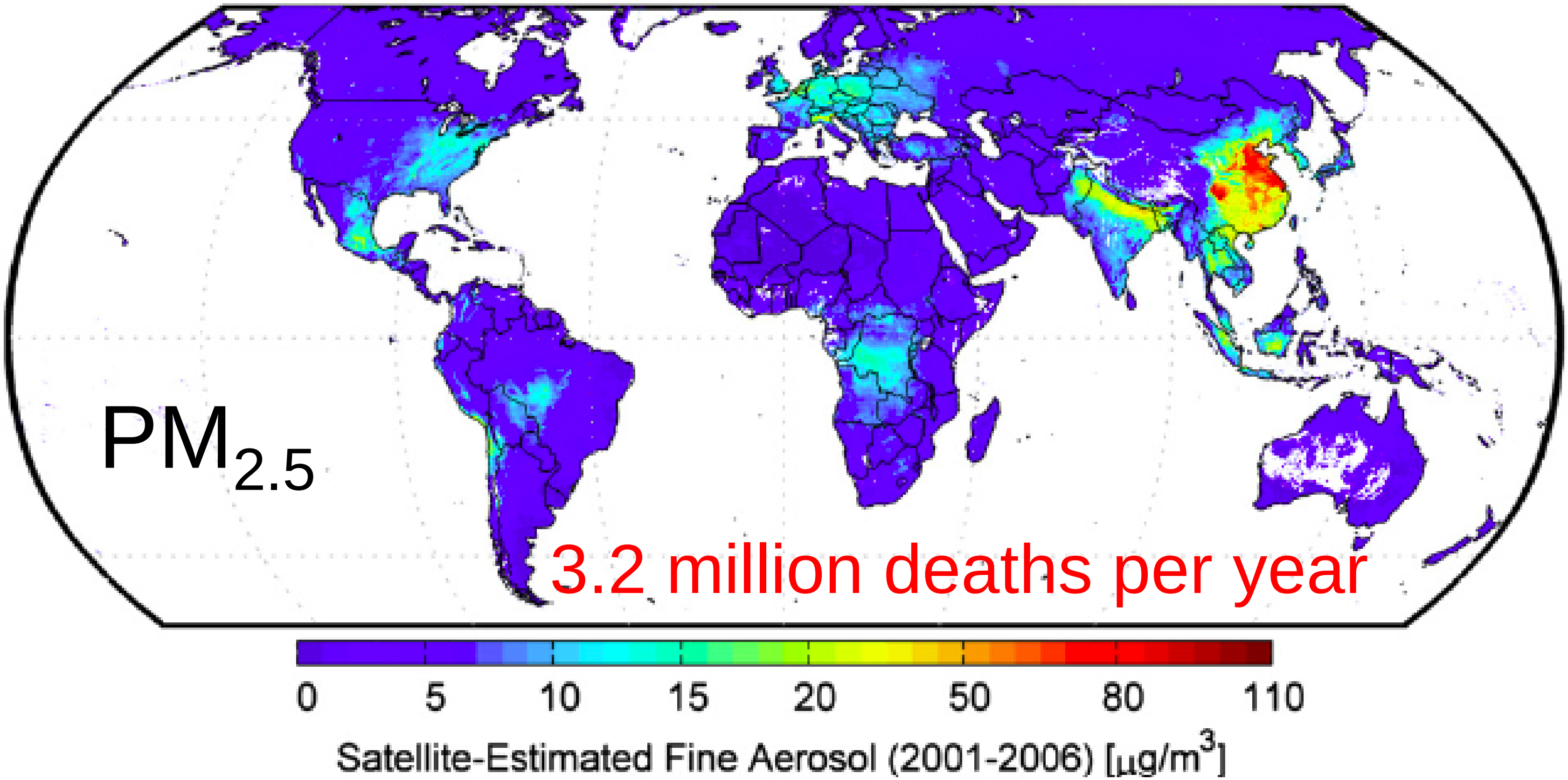
mortality rates about 1% for every 5 µg/m^3 increase in $PM_{2.5}$



Crouse et al EHP May 2012

Greg Evans, University of Toronto

$PM_{2.5}$ exposure and cardiovascular mortality: Global



Adult Mortality 8% (5.5-10.5)

Cardiopulmonary disease 12.8% (5.9-18.5)

Evans J et al Env Res 2013

Greg Evans, University of Toronto

Air Quality and Visibility

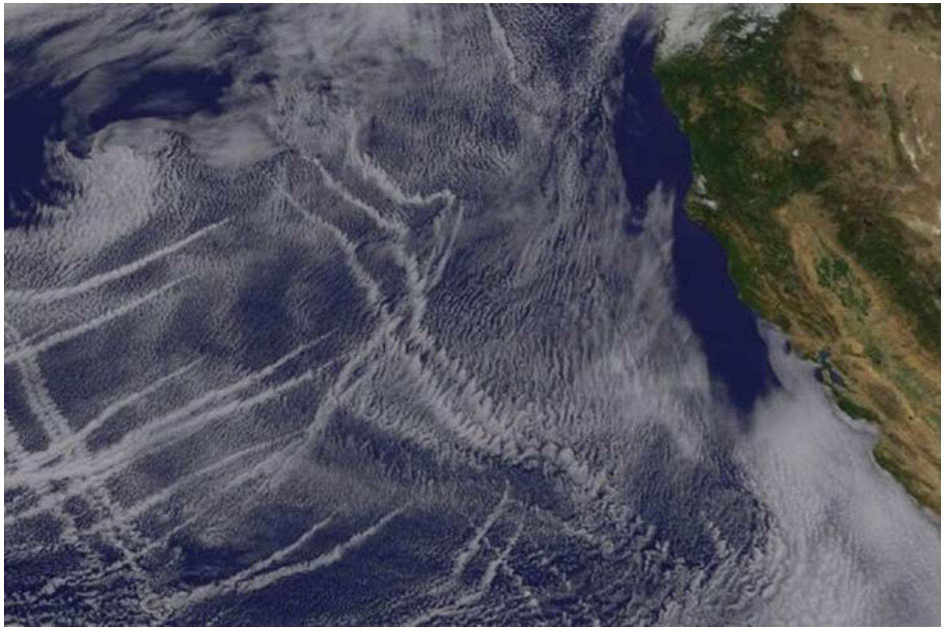
Aerosols in the atmosphere absorb and scatter light which reduces visibility

Jeff Brook, Environment Canada

How do aerosols affect climate?

Aerosols directly affect the global climate by absorbing and scattering solar radiation.

Aerosols indirectly affect the global climate by changing the properties of clouds - increases their albedo and lifetime.



- example of indirect effect is ship tracks

http://www.wjla.com/pictures/2011/07/daily-eye-wonder---july-2011/ship-contrails-in-pacific-5508-366.html

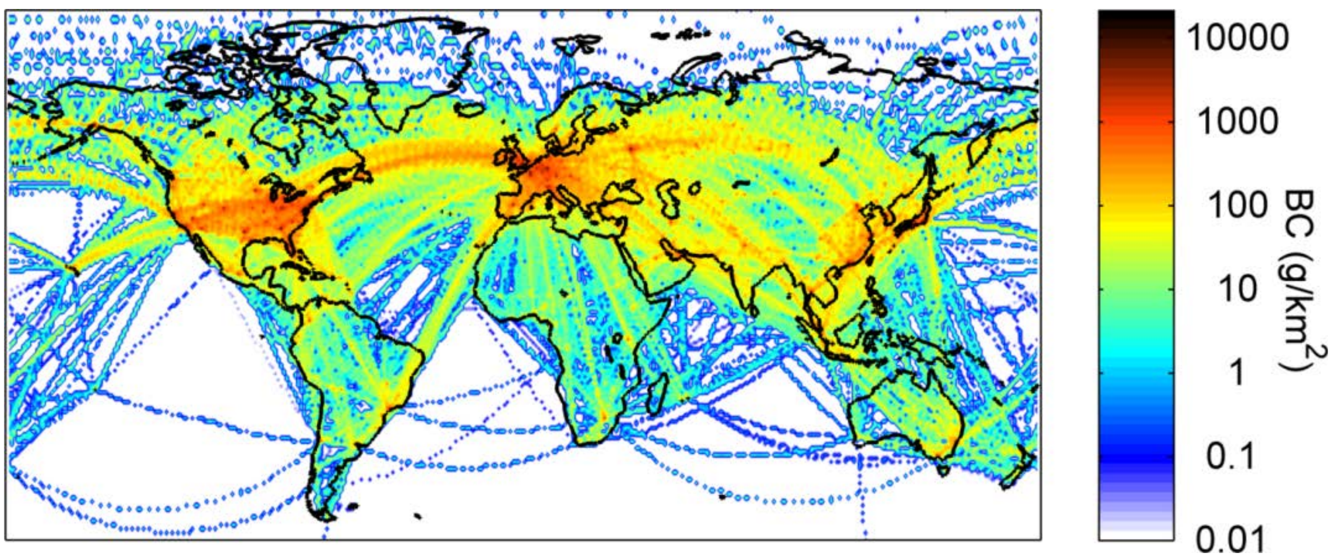
Allan Bertram, University of British Columbia

Global aircraft black carbon (BC) emissions

1960’s

1980’s

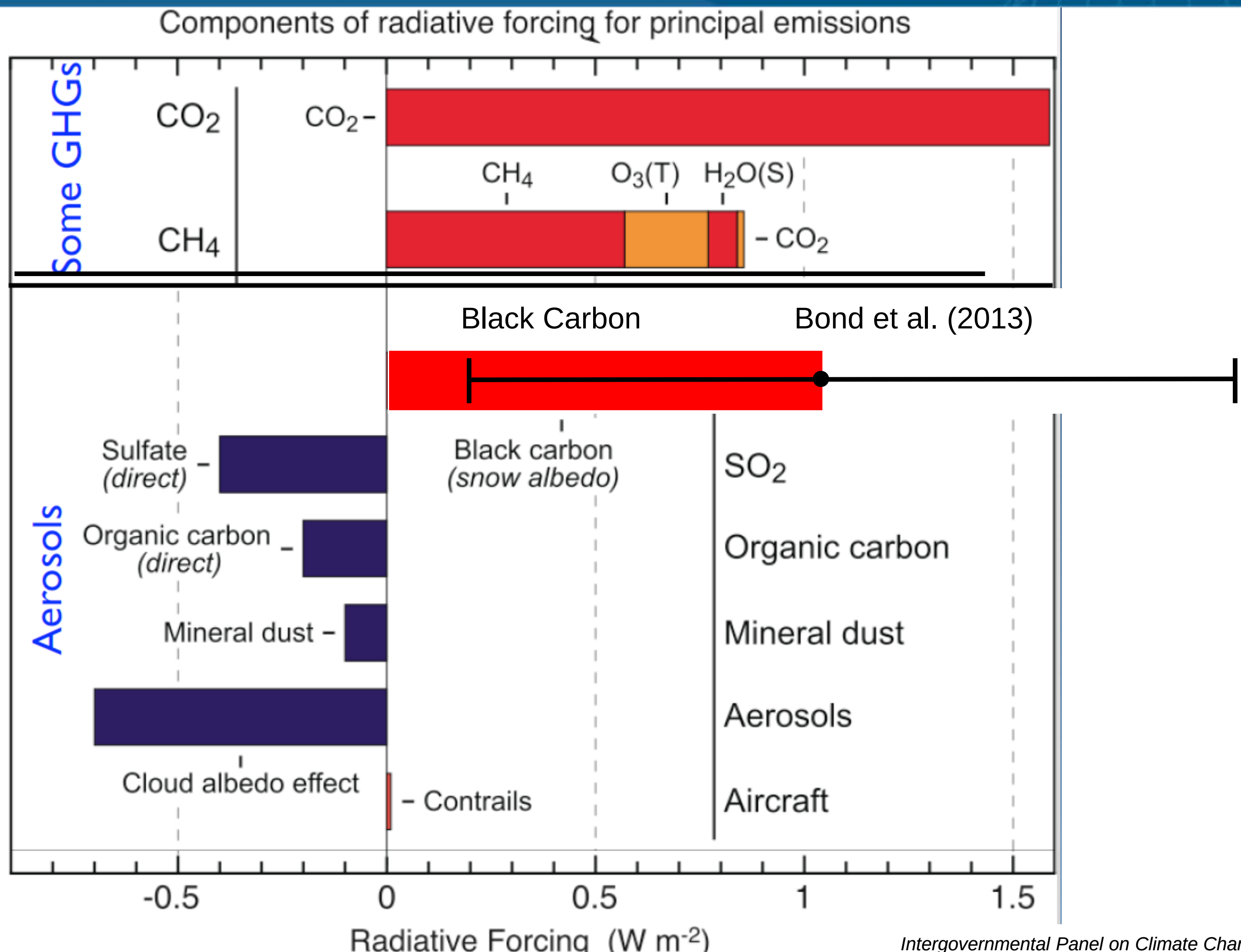
2000’s



Stettler et al., (2013). Environ. Sci. Technol. doi.org/10.1021/es401356v

Adam Boies, University of Cambridge

Relative Effect of Aerosols on Climate



Intergovernmental Panel on Climate Change (2007)

Impacts of Black Carbon

- BC is the most light-absorbing nano-aerosol
- BC absorbs 680x more energy by mass than CO_2
- BC is a key contributor to global warming
- BC effects are stronger in sensitive regions, i.e. faster ice and snow melt in the Canadian Arctic
- BC mitigation could rapidly slow the rate of climate change, by up to 40% within 20 years

For BC and related combustion emissions, on a global scale

- “the adoption of aggressive standards by 2015 would annually prevent the deaths of 200,000 people, save 13 million tons of grain and $1.5 trillion in health damages after 2030.”

Shindell et al, 2011, Nature Climate Change, 1, 59-66

What needs to be measured?

- regulated gaseous pollutants are specific
  - CO_2, CO, SO_2, NO_x, HC, etc.
  - measurement of gaseous concentration
- current regulatory focus for PM is mass concentration in most jurisdictions
- Europe has added number concentration for on-road vehicle emissions
- health and environmental researchers and policymakers are asking for more specificity on PM
  - size and size distribution
  - composition
  - surface area and surface reactivity
  - optical properties (absorption and scattering)

Measurement Issues (I)

Traceability

- many instruments offer no opportunity for traceability
- filter-based mass can be traceable
  - issues with sensitivity (mass of particulate vs. mass of filter)
  - issues with filter artifacts
    - gaseous adsorption
    - fibre loss
    - less than 100% removal efficiency
  - issues with size cutoff
    - impactors and cyclones do not cut sharply at threshold (i.e. $PM_{2.5}$)
- number concentration can be made traceable (sort of)

Measurement Issues (II)

Reliability and Repeatability

- difficult to establish

Uncertainty

- large uncertainties (can be order of magnitude in number, factor of 2 in mass)

Reference Materials

- airborne particulate RMs don't exist

Representativeness

- all ex-situ methods suffer from sampling issues
  - how representative is the sample at the measurement location of the airborne particulates?
    - losses, agglomeration, evaporation/condensation

Measurement Issues (III)

Measuring properties with different methods

- most instruments are proprietary
  - each manufacturer implements a different measurement principle
- difficult to intercompare results obtained with different instruments
- examples
  - size
    - mobility diameter, aerodynamic diameter, geometric diameter, radius of gyration
  - black carbon mass
    - directly measured, or inferred from optical absorption, extinction, or emission measurements

Measurement Issues (IV)

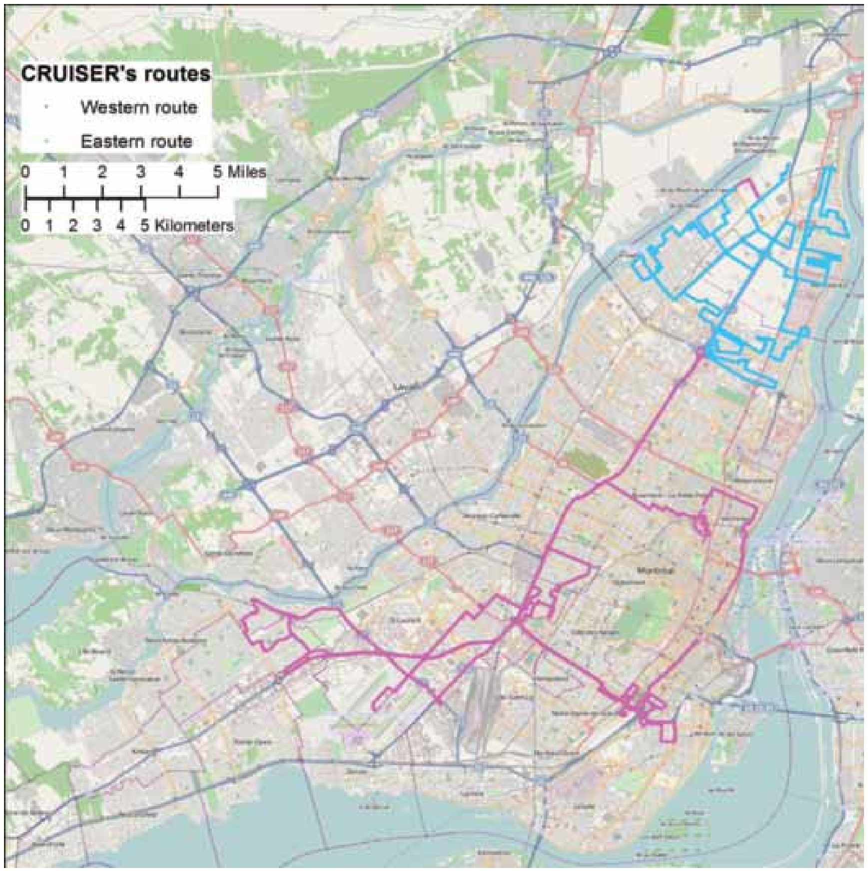
Measuring specific properties with a myriad of interferences

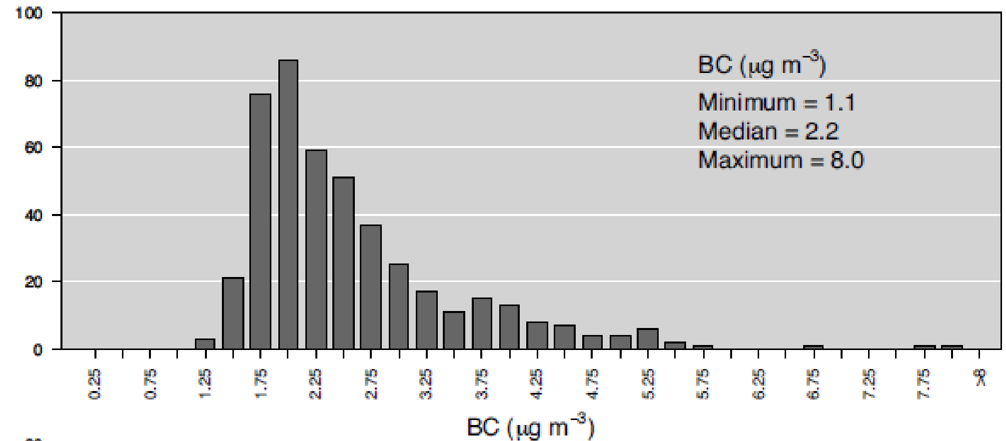
- selectivity
  - how does one measure properties of one component of PM when many others are present?
- sensitivity
  - atmospheric concentrations are often very low (<1 µg/m^3)
- gas composition
  - can be highly variable
  - can influence measurement
- morphology
  - spherical particles vs. fractal aggregates
- single particle vs. ensemble measurements
- variations over time, elevation, temperature, humidity, sunlight, etc.

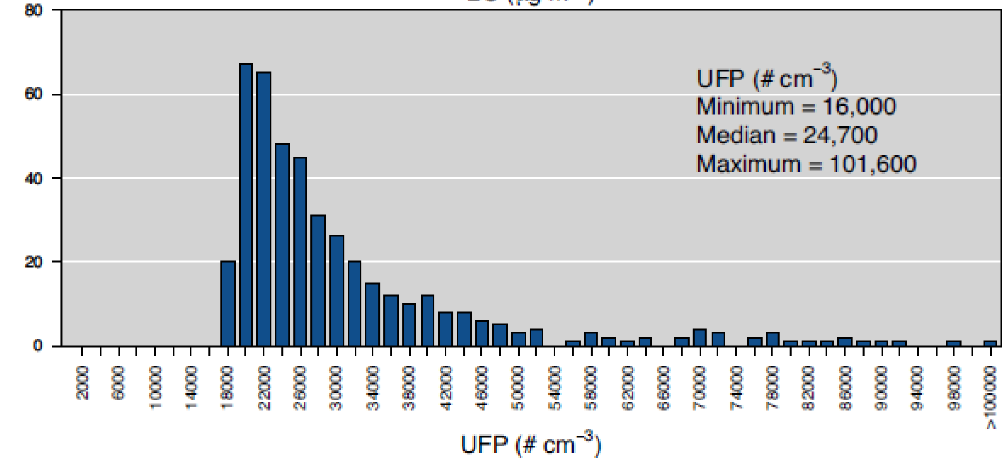
What is the Canadian perspective on research and monitoring of airborne particulates?

Jeff Brook, Environment Canada

CRUISER Mobile Lab Survey in Montreal (2009)





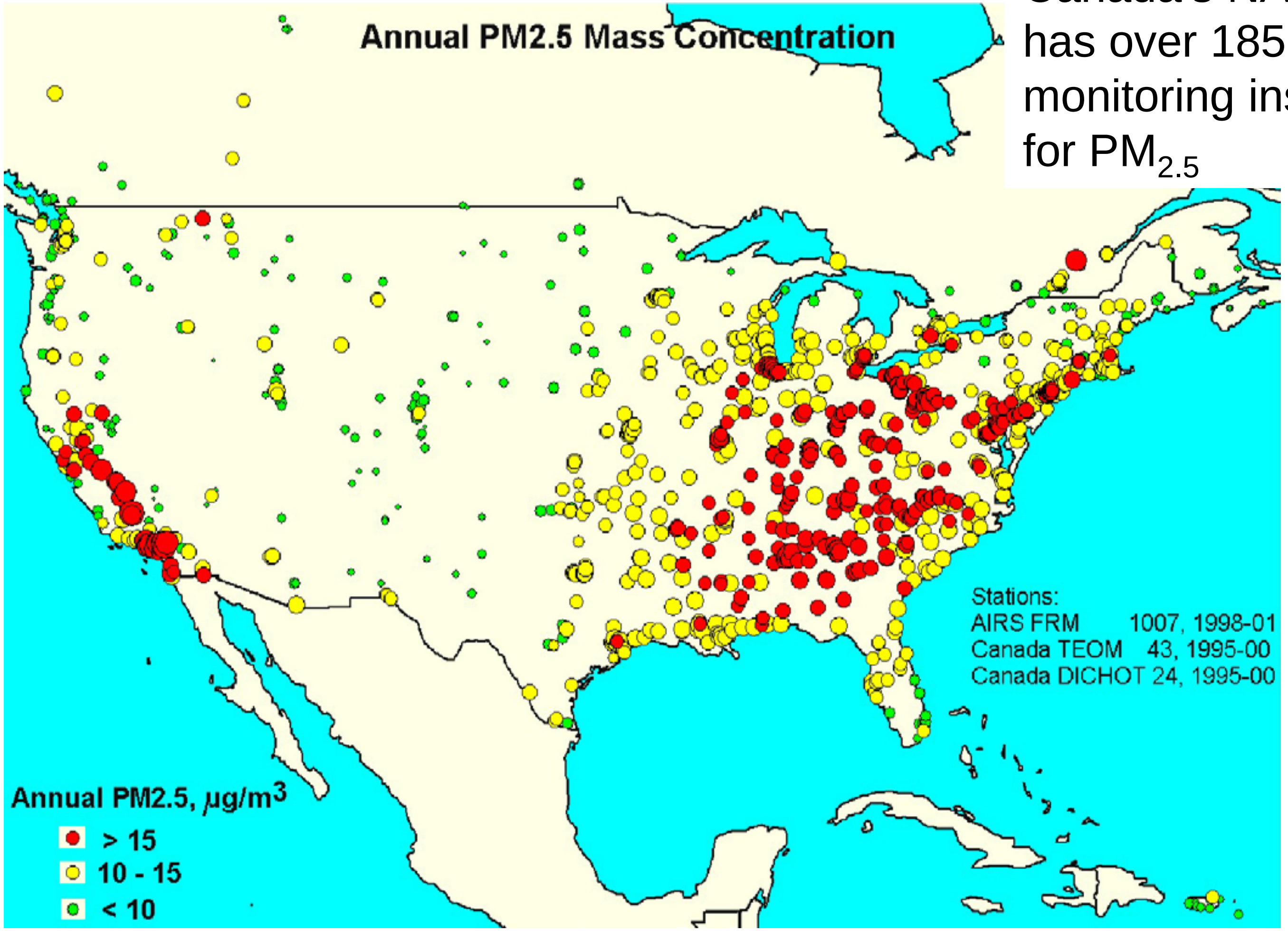


Jeff Brook, Environment Canada

NRC·CNRC

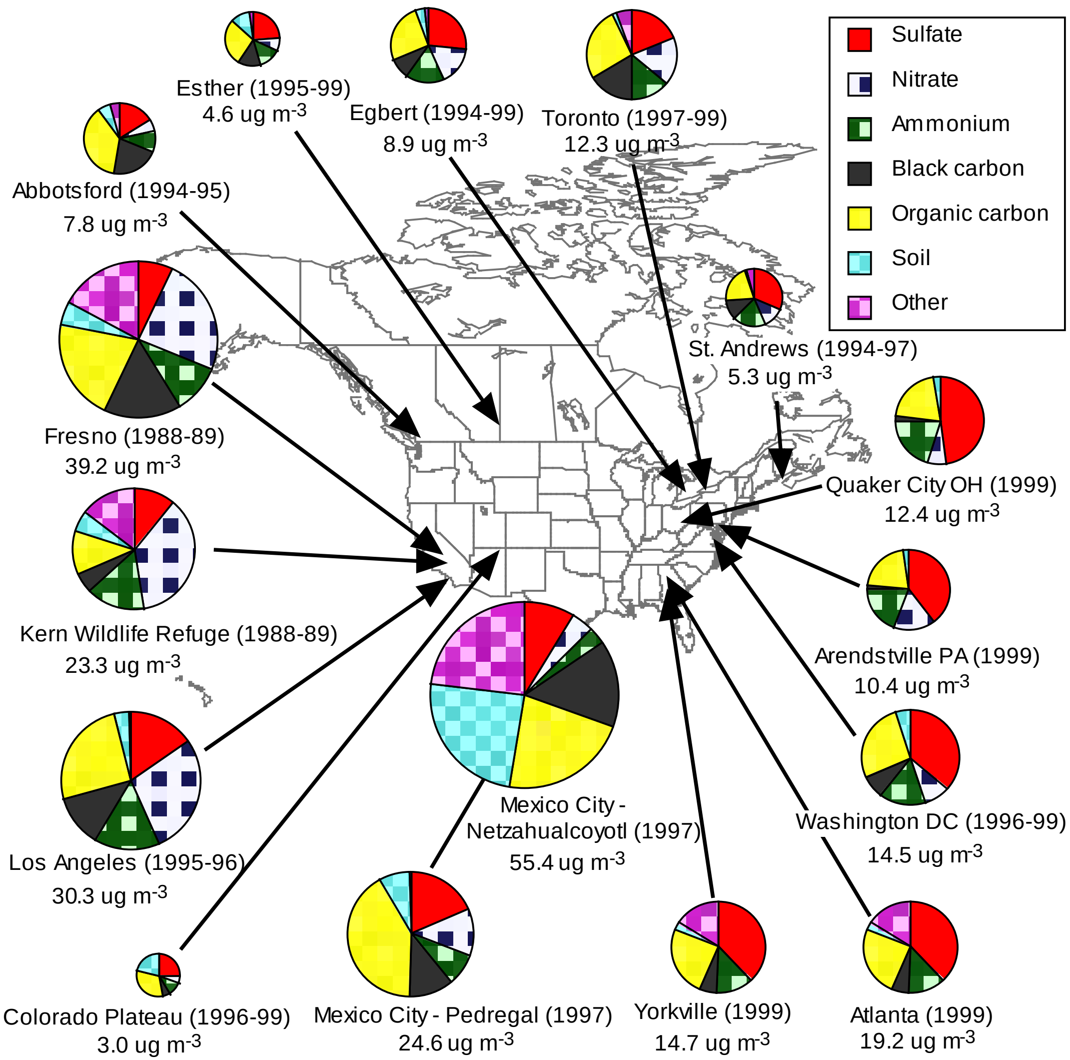
North American $PM_{2.5}$ Measurements

Canada's NAPS network has over 185 real-time monitoring instruments for $PM_{2.5}$



Jeff Brook, Environment Canada

$PM_{2.5}$ Composition in North America

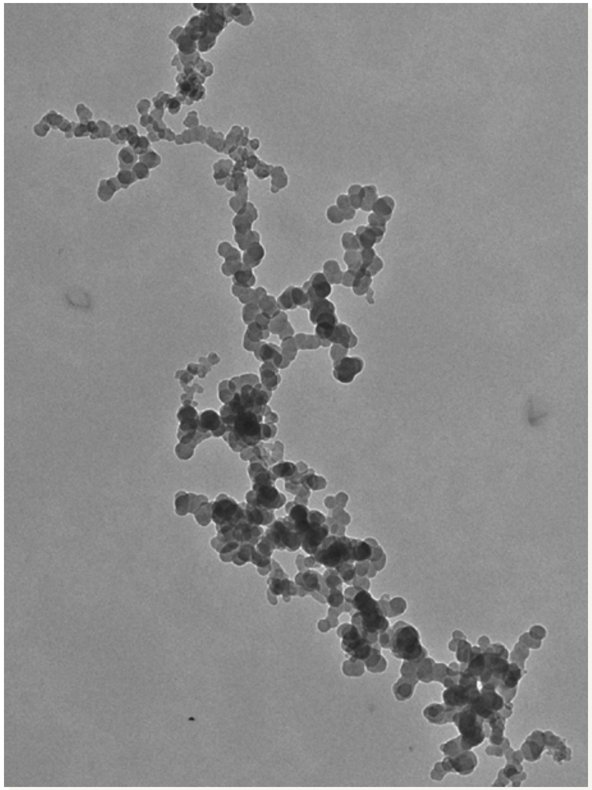


Jeff Brook, Environment Canada

What is Canada doing about the measurement of black carbon?

"Black Carbon is a distinct type of carbonaceous material that is formed primarily in flames, is directly emitted to the atmosphere, and has a unique combination of physical properties"

- strongly absorbs visible light
- is refractory with a vaporization temperature near 4000 K
- exists as an aggregate of small spheres
- is insoluble in water and common organic solvents



Bond et al., "Bounding the role of black carbon in the climate system: A scientific assessment,"Journal of Geophysical Research – Atmospheres, 2013

Confusion around BC definition

refractory carbon

brown carbon

elemental carbon

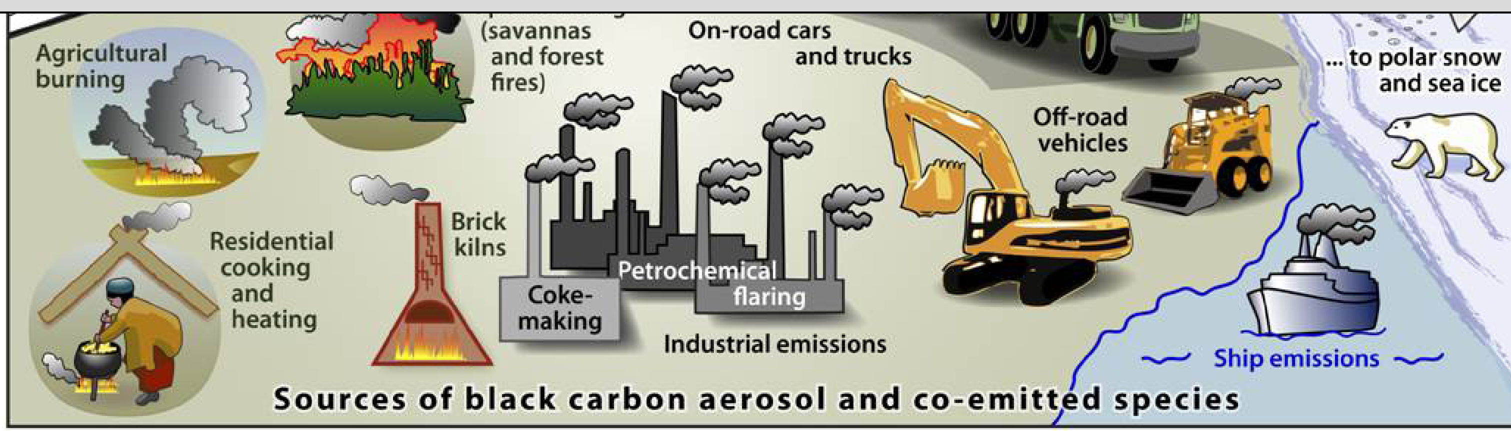
black carbon

soot carbon

light absorbing carbon

Black Carbon (BC) Aerosol Processes in the Climate System

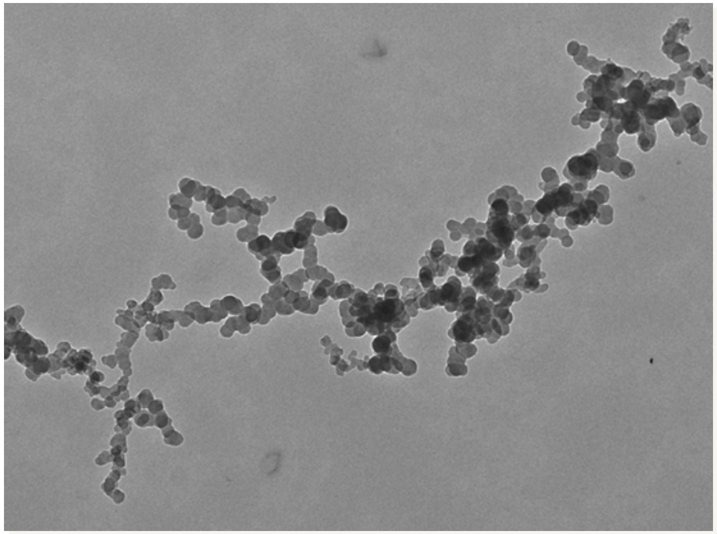
- overall impact of BC estimated as + 1.1 Wm^{-2}
  - CO_2 and CH_4 are 1.56 and 0.86, respectively
  - this is higher than previously estimated
  - BC is the 2nd most significant climate forcer
- recognized by Climate and Clean Air Coalition (CCAC) as a significant short lived climate pollutant
- diesel engines produce 70% of BC emissions in NA
- engine technologies and fuels are changing and there is a need to understand the impact of these new changes on BC emissions and emission measurements



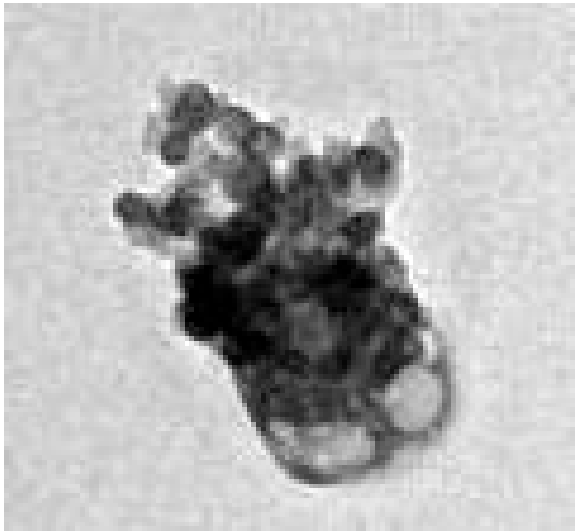
T. C. Bond et al., Bounding the role of black ... nospheres, doi: 10.1002/jgrd.50171, 2013.

Black Carbon Aging in the Atmosphere

- as BC surface oxidizes in the atmosphere, coatings will be deposited
  - – lead to collapse, changing the morphology of the particles
- uncertainty around how these coatings and morphology changes influence the radiative properties of BC



freshly emitted BC – fractal morphology



aged BC – compact structure

Examples of BC and PM measurement instruments

Laser Induced Incandescence

Thermal Optical EC/OC Analyzer

Gravimetric

Centrifugal Particle Mass Analyzer

HR-TEM

Electrostatic Precipitator

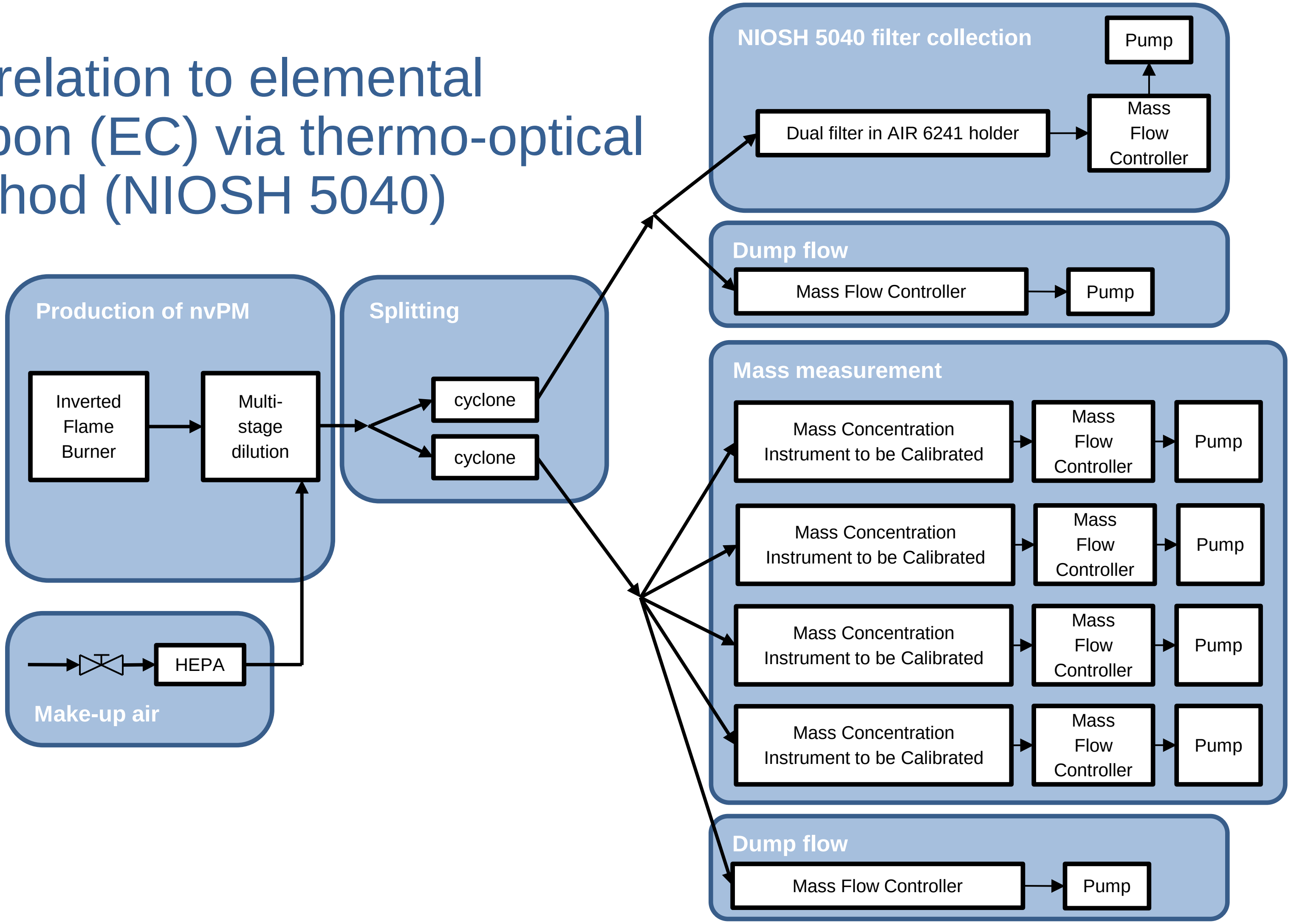
Fast Particle Mobility Size Spectrometer

Scanning Mobility Particle Sizer

Condensation Particle Counter

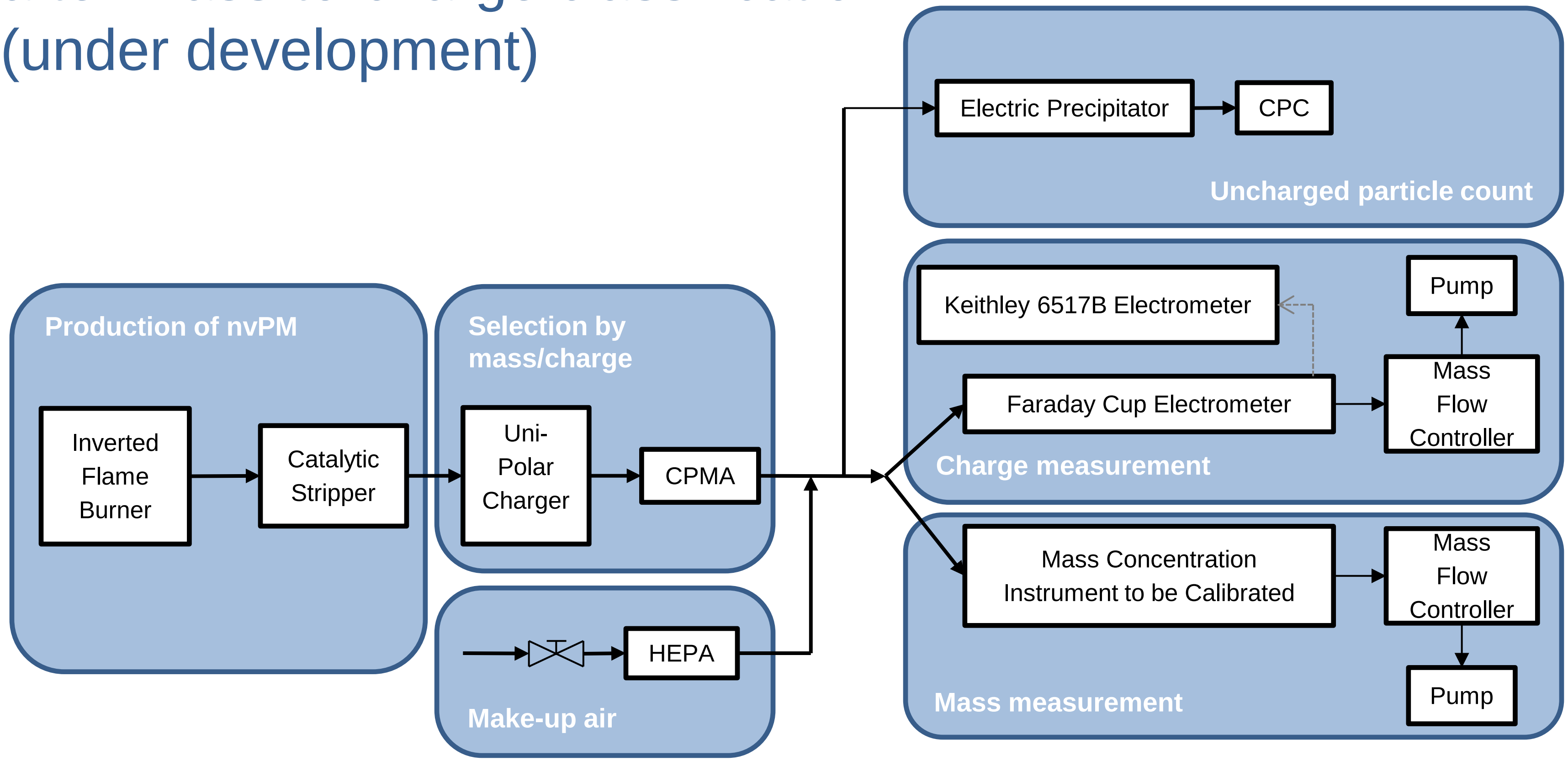
Development of BC Mass Calibration (I)

Correlation to elemental carbon (EC) via thermo-optical method (NIOSH 5040)



Development of BC Mass Calibration (II)

Correlation to electrical charge after mass-to-charge classification (under development)



NRC·CNRC

Summary (I)

Airborne particulate matter has significant, detrimental effects on health, visibility, and climate

- $PM_{2.5}$ mass concentration measurements, while important, are a poor overall indicator of these effects

PM metrology is required

- to improve reliability and repeatability of measurements, and to reduce uncertainty
  – critically important to climate change modelling
  – necessary to improve association between health effects and PM properties
- for sound policy decisions and regulations

Summary (II)

Quality of measurements and intercomparability need to be improved

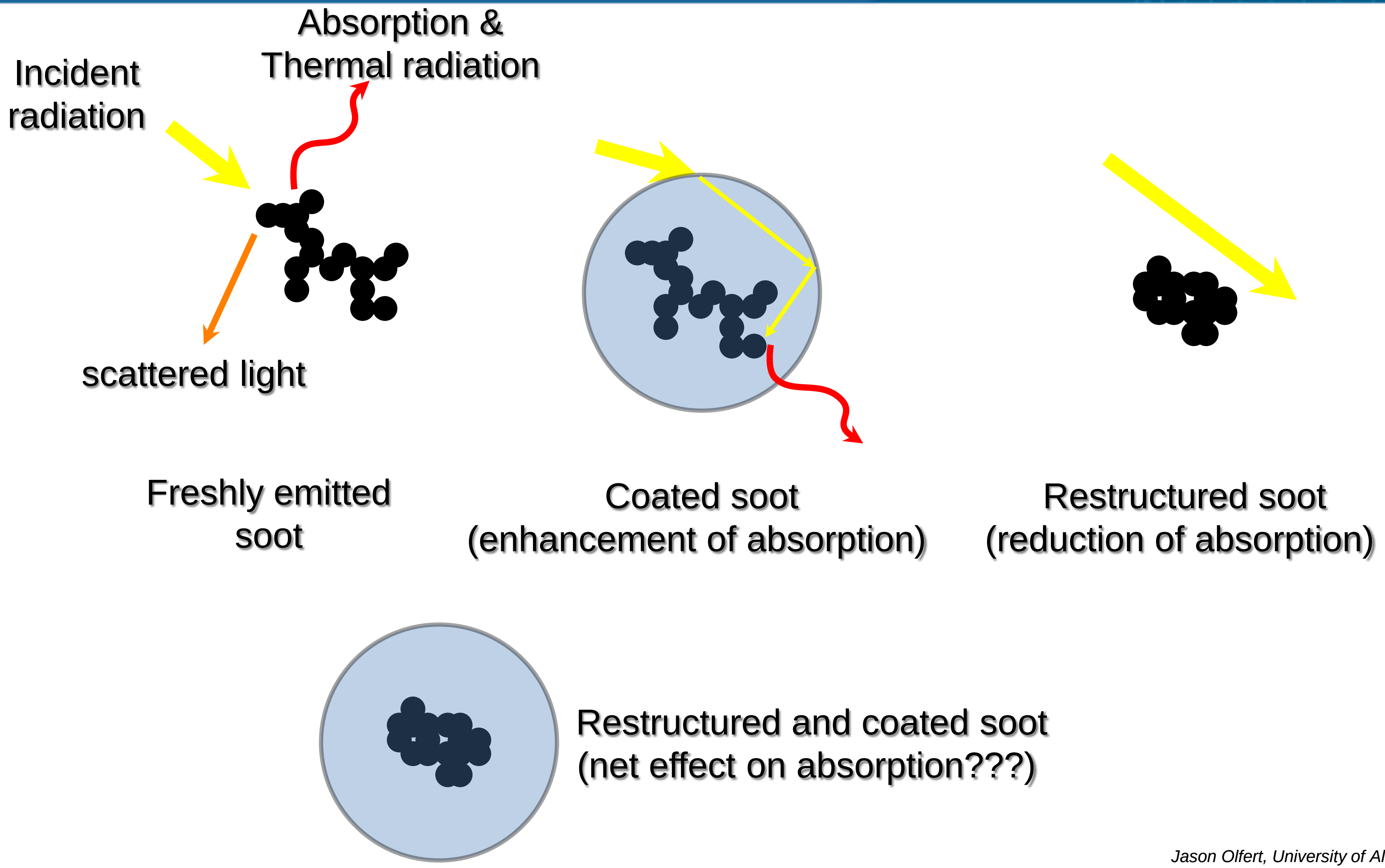
- size and size distribution
- composition
- surface area and surface reactivity
- optical properties (absorption and scattering)
- mass of smaller size fractions ($PM_{1.0}$)

Black Carbon is one of the best PM targets due to co-benefits in reducing climate forcing and improving human health

Thank you

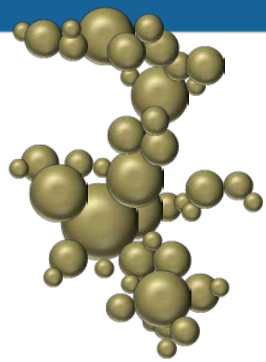
Dr. Gregory J. Smallwood
Program Leader, Measurement Science for Emerging Technologies
phone: 613-993-1391
e-mail: greg.smallwood@nrc-cnrc.gc.ca
web: www.nrc-cnrc.gc.ca

Variations in Optical Absorption



Jason Olfert, University of Alberta

Black carbon metrics of importance



Black carbon often consists of highly non-spherical agglomerates of non-uniform primary particles

Radiative forcing	$\propto$ **Mass** concentration of BC
Cloud condensation	$\propto$ **Number** concentration of BC
Chemical reactions	$\propto$ **Surface area** concentration of BC
Health impacts	$\propto$ **Mass, number and surface** area concentration of BC
Particle settling	$\propto$ **Mass** of individual particle
Advective transport	$\propto$ Non-spherical drag coefficient, **dynamic shape factor**

Adam Boies, University of Cambridge

BC Characterization – not just mass and number

common indicators of interest

- mass concentration (environment)
- number concentration (health)

additional parameters important to understand the true impacts of BC

- spectral light absorption characteristics
- detailed morphology
- active surface area (chemical/thermal)
- primary particle diameter distribution
- aggregate size distribution
- optical properties
- volatile fraction
- chemical composition

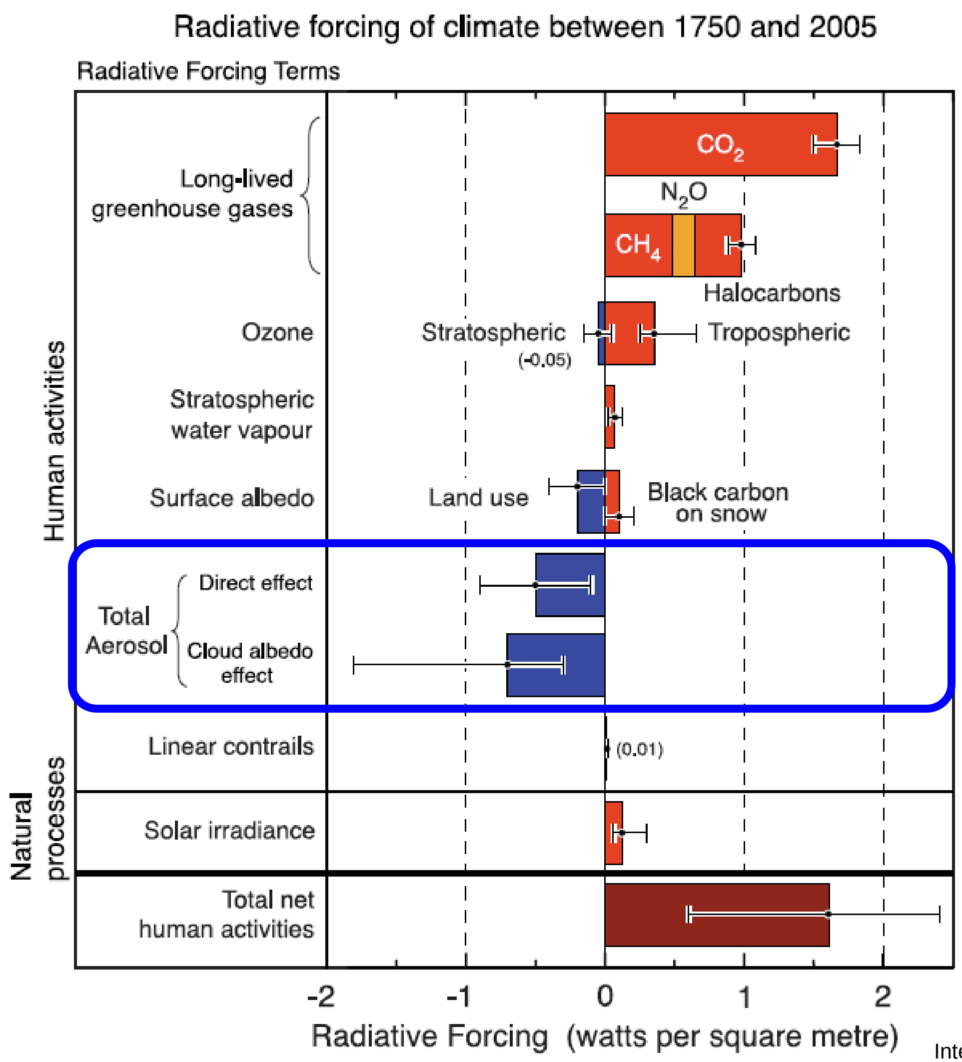
improved characterization of all parameters is important to reducing the uncertainty associated with black carbon's role in climate forcing

Activities Known to Emit Carbon Particles

Sources of Carbon Particles	Biogenic	Anthro-pogenic	Black Carbon	Organic Carbon
Wood Combustion (stoves, wild fires)	●	●	●	●
Gasoline vehicles		●	●	●
Heavy duty diesel (on-road, off-road, ships)		●	●	●
Tire wear, brakes, road dust		●	●	●
Leaf litter and leaf waxes, spores, bacteria	●			●
Aircraft		●	●	●
Natural gas combustion		●	●	●
Tobacco smoke		●	●	●
Steel production and coke ovens		●	●	●
Fuel oil boilers		●	●	●
Cooking of meat, vegetables, use of cooking oil		●	●	●
Coal combustion		●	●	●
Road paving		●		●
Roofing tar pots		●	●	●

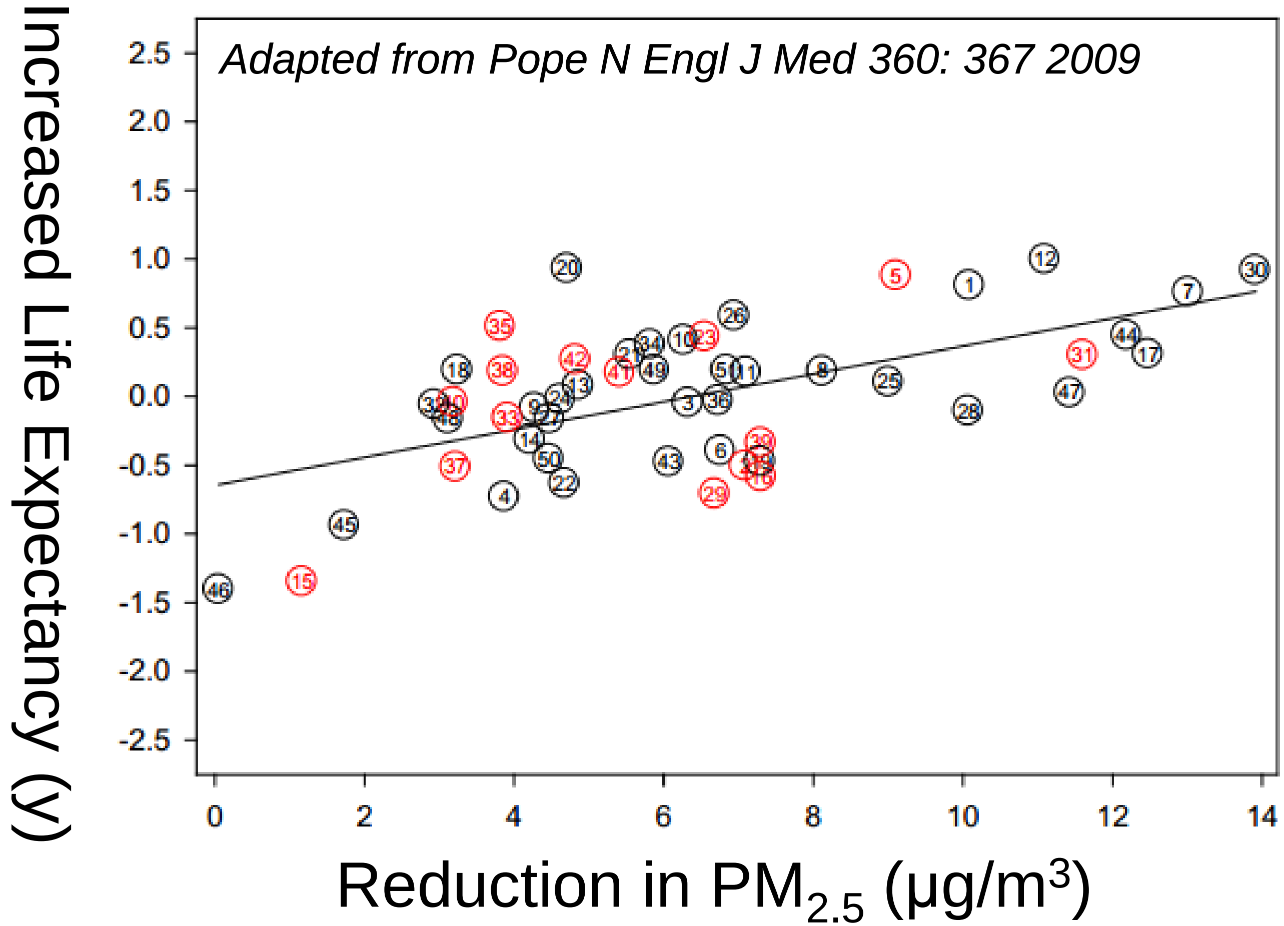
Jeff Brook, Environment Canada

Relative Effect of Aerosols on Climate



Intergovernmental Panel on Climate Change (2007)

Trend 1: Is improving air quality benefiting health?

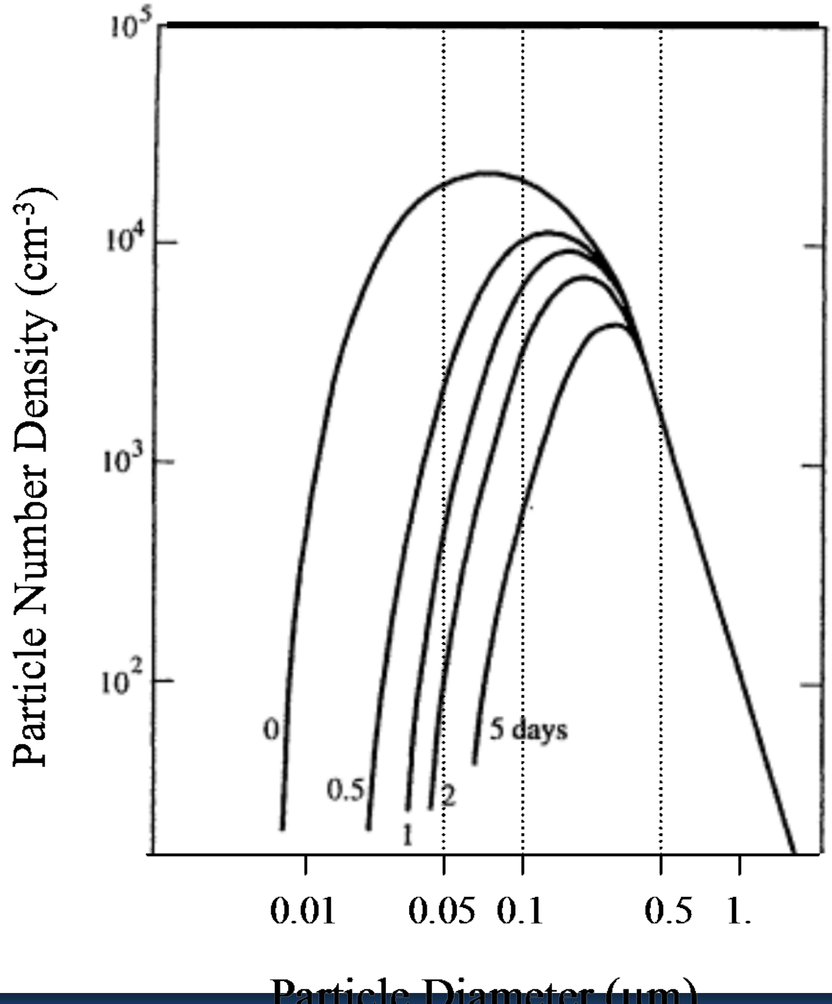


51 US Cities
1980-2000

Reduced pollution yields increased life expectancy

Lifetime of Ultrafine Particles

Change in distribution due to coaggulation

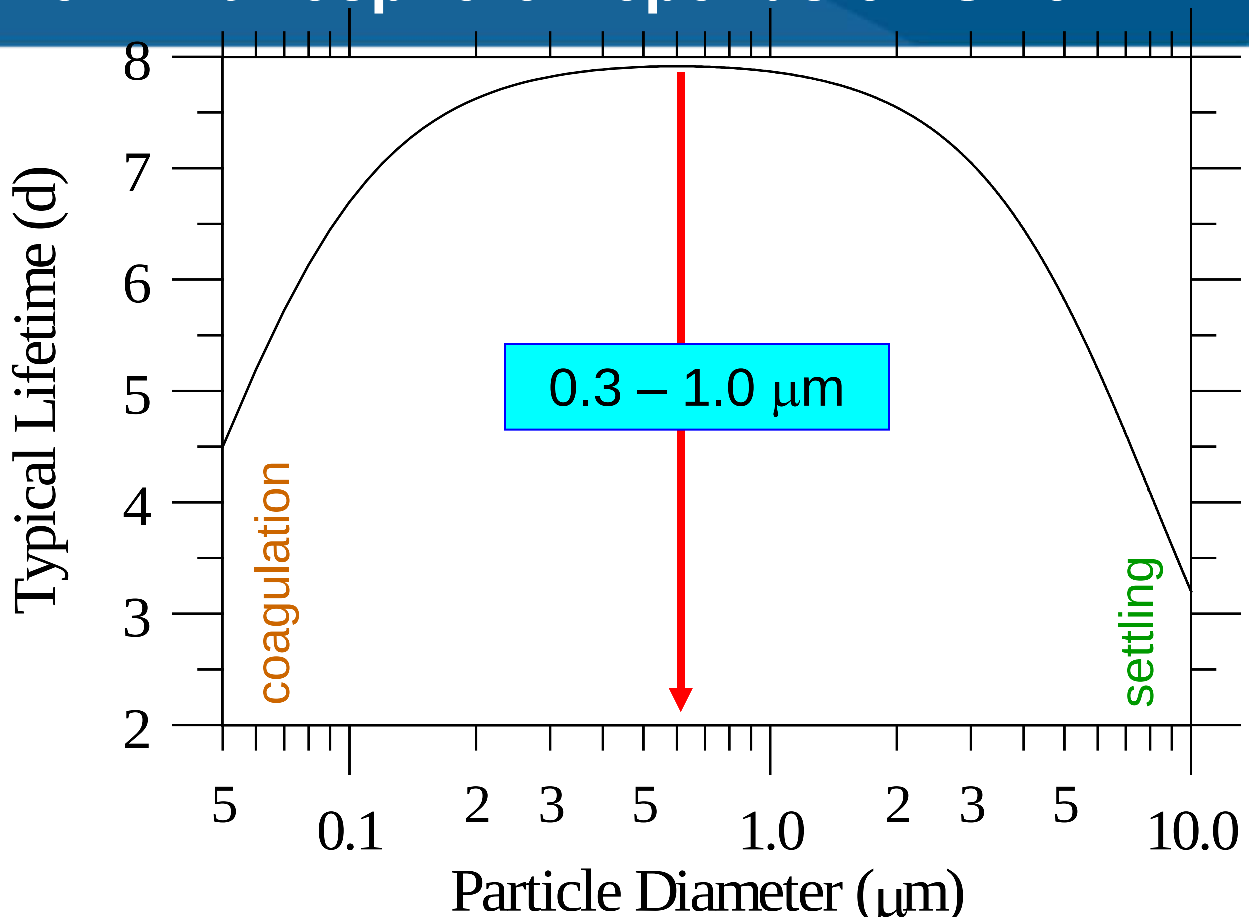


- The number of nuclei mode particles (<10 nm) last less than half a day
- Ultrafine particle number reduces by at least an order of magnitude in a day and a half
- Beyond 2 days the bulk of the particles have grown into the accumulation model
- Result: total number reduces and mass concentrates in accumulation model

Jeff Brook, Environment Canada

NRC·CNRC

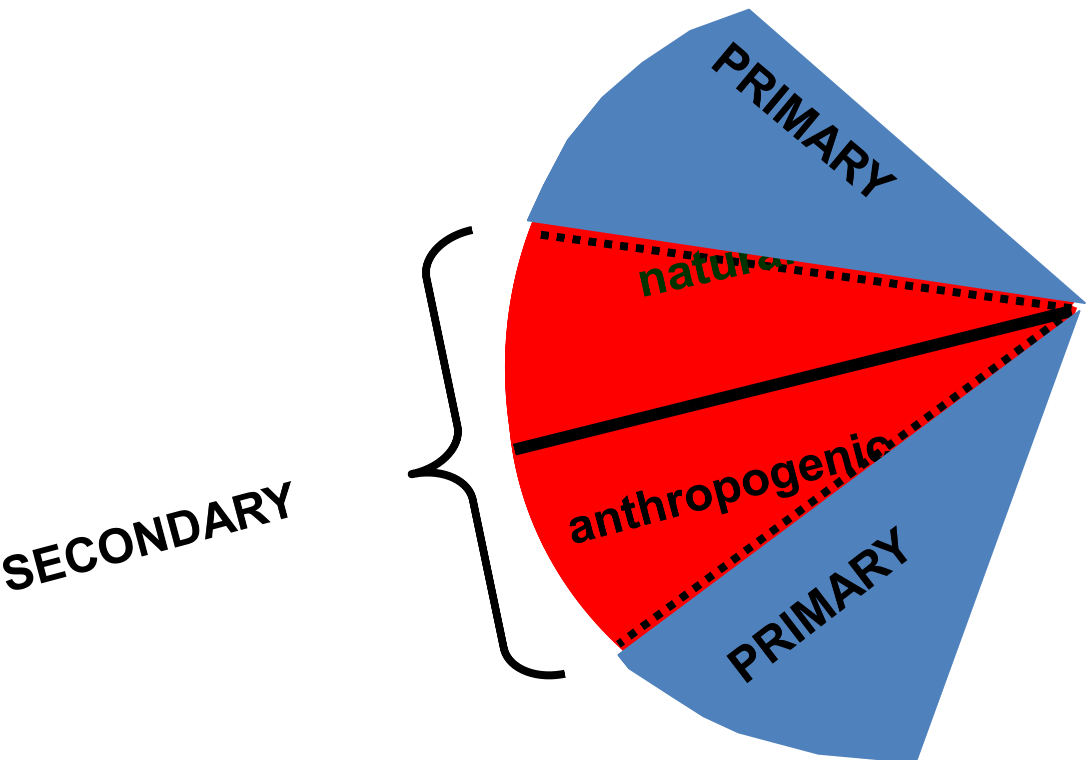
Lifetime in Atmosphere Depends on Size



- Wet and dry deposition are the main loss mechanisms
- Deposition velocity is slow (0.1-1.0 cm s^{-1}) and interception of rain drops is relatively inefficient

Jeff Brook, Environment Canada

General Apportionment of Organic Carbon (OC)



BIOGENIC
(primary and secondary)

- cannot be controlled, but must be quantified relative to anthropogenic fraction

ANTHROPOGENIC

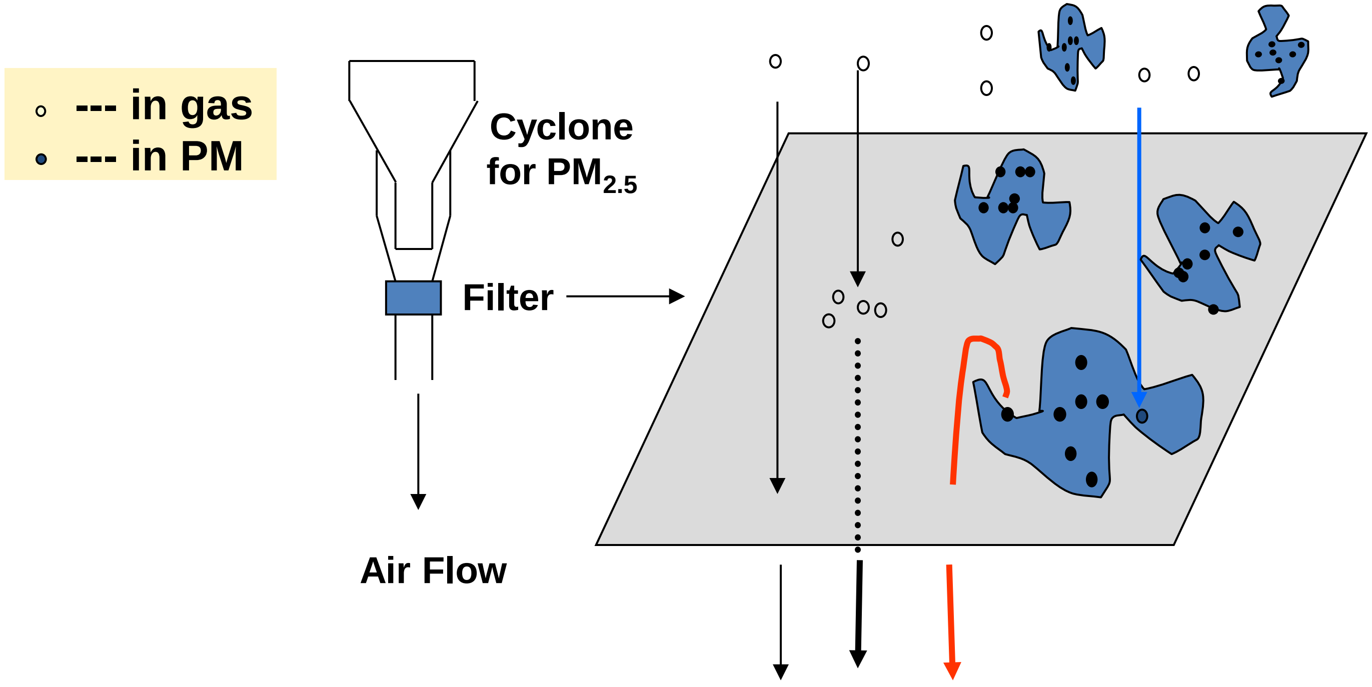
- can be controlled
- need to know relative amounts of primary and secondary OC
- need to know main sources of both fractions
  "specific apportionment"

OC is the least understood fraction

Jeff Brook, Environment Canada

Sampling Artifacts due to Semi-Volatiles

Molecule Interactions during Air Sampling

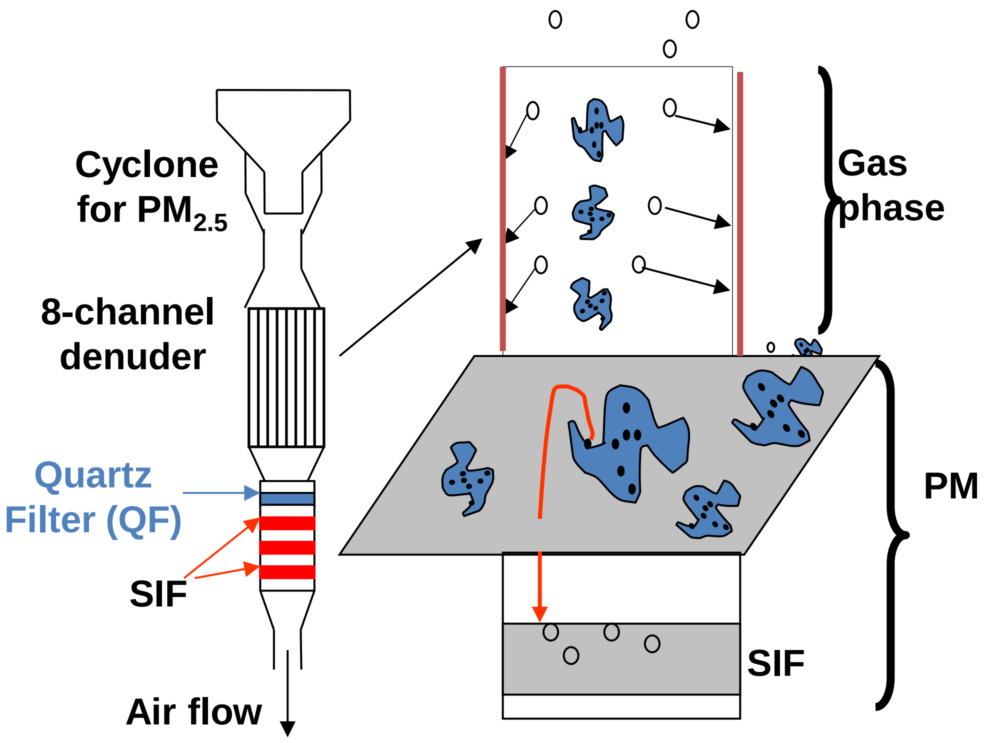


Traditional Filter Pack (FP) Sampler

Jeff Brook, Environment Canada

Sampling approach for reducing artifacts

◦ --- in gas
• --- in PM



Integrated Organic Gas and Particle Sampler (IOGAPS)

Jeff Brook, Environment Canada

Why They are Important (Continued)

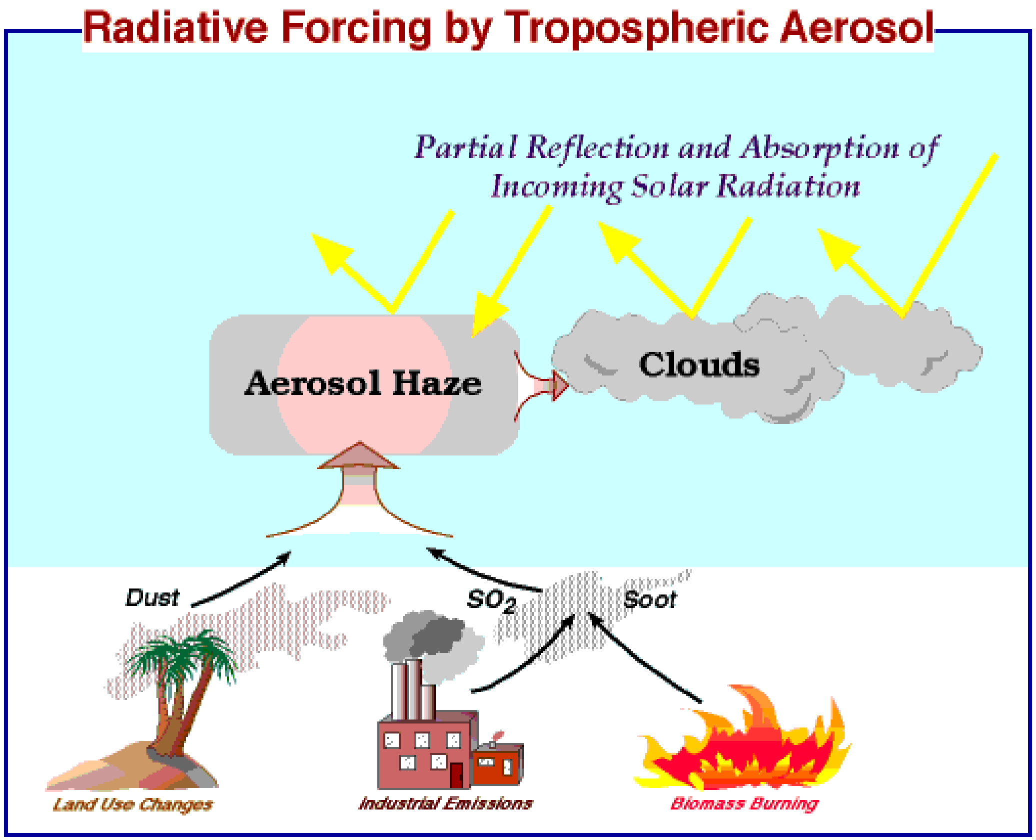
Modify the Earth's Climate

Indirectly Modify Climate

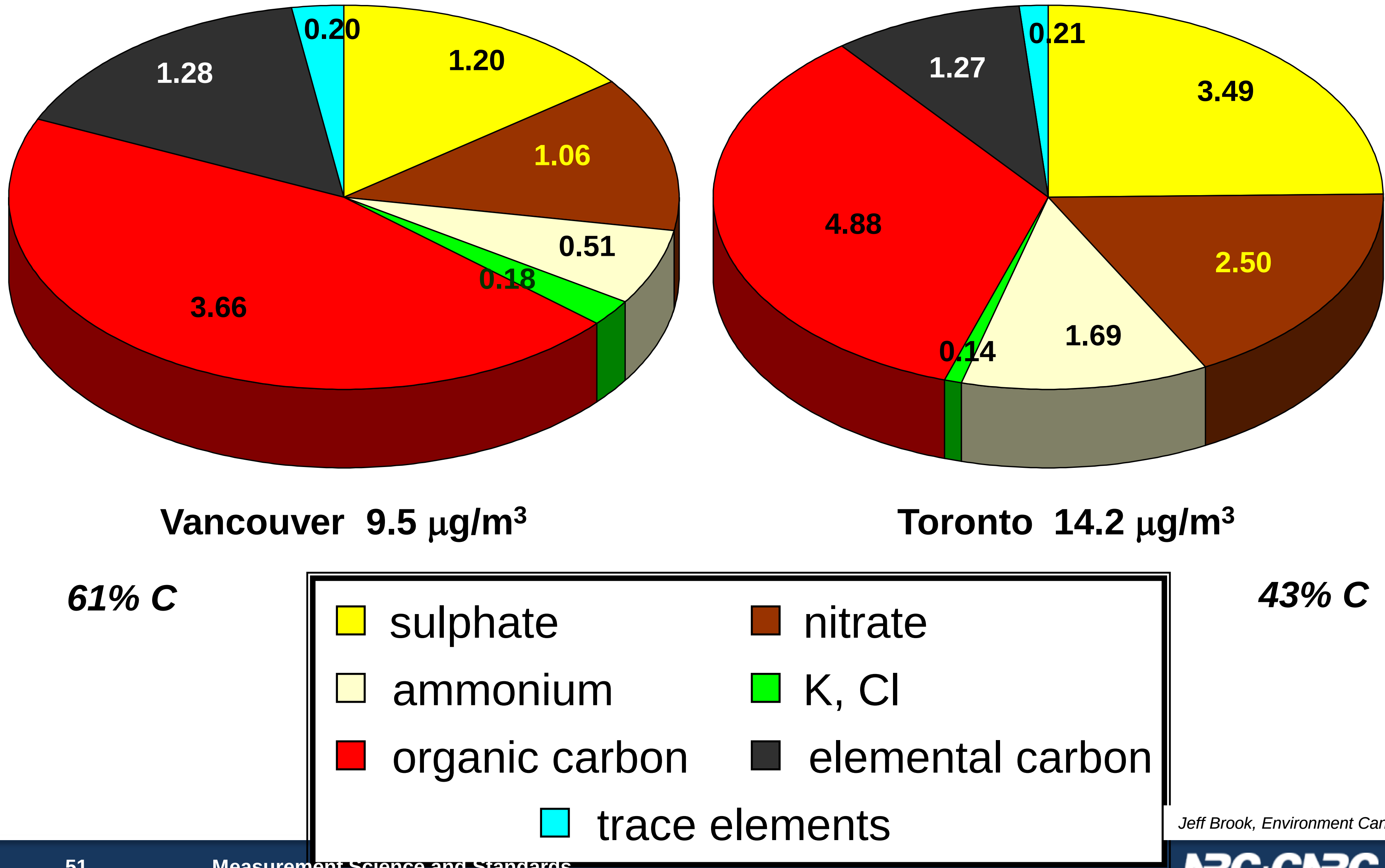
- by acting nucleation sites for clouds
- If act as nucleation sites they can change the frequency of clouds and the size of cloud droplets → change the amount of light the clouds scatter

Key point: Aerosols can have a large effect on the Earth's radiation budget → The radiative forcing by Anthropogenic aerosols is believed to be the same order of magnitude as the radiative forcing by CO_2

Key point: To understand and predict climate change and *make effective policy decisions on climate change* need to understand atmospheric aerosols and their role in climate!!

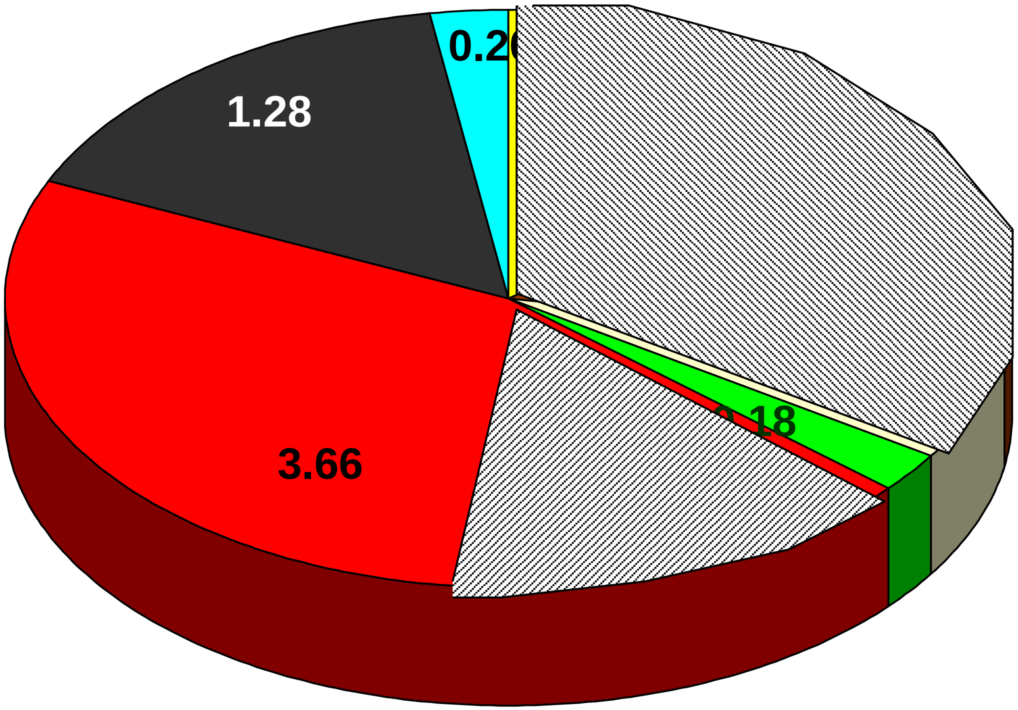


Comparison of Two Canadian Cities



Jeff Brook, Environment Canada

Amount of $PM_{2.5}$ from Secondary Formation



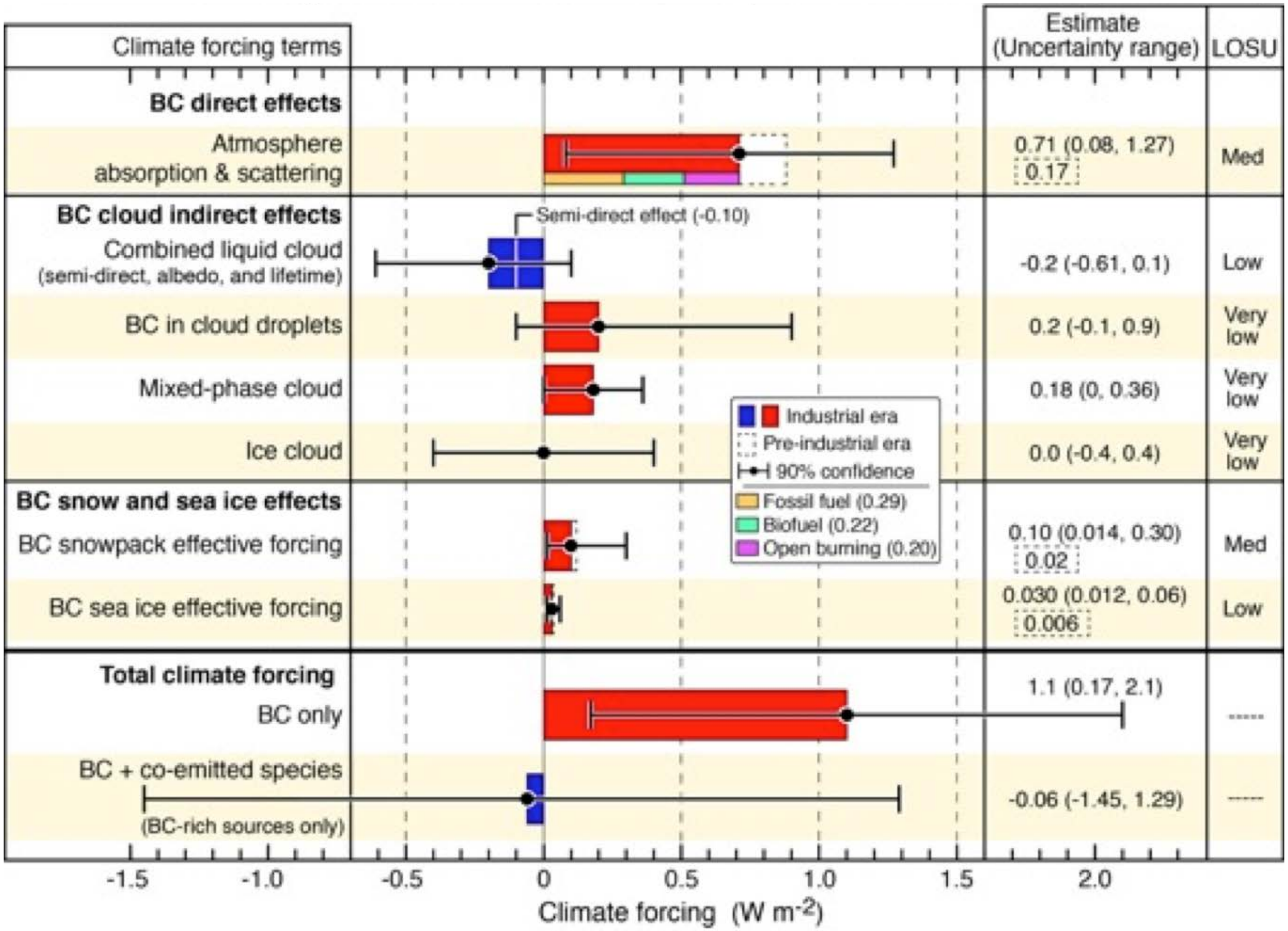
Vancouver 9.5 μg/m³

Sulphate	1.2
Nitrate	1.1
Ammonium	0.5
20% of OC	0.75
	3.5

37% of $PM_{2.5}$
is secondary

Jeff Brook, Environment Canada

Global Climate Forcing of Black Carbon



T. C. Bond et al., Bounding the role of black carbon in the climate system: A scientific assessment, Journal of Geophysical Research-Atmospheres, doi: 10.1002/jgrd.50171, 2013.